

THE ECO OFFICE: Dynamic and Homeostatic Façades inspired by
BIOMORPHISM, BIOMIMICRY, AND BIOPHILIA

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May 2013

Submitted towards the fulfillment of the requirements for the Doctor of Architecture degree.

School of Architecture
University of Hawai'i

Doctorate Project Committee

Stephen Meder, Chairperson

David Garmire

Andrew Kaufman

Elizabeth Lockard

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We certify that we have read this Doctorate Project and that, in our opinion, it is satisfactory in scope and quality in fulfillment as a Doctorate Project for the degree of Doctor of Architecture in the School of Architecture, University of Hawai‘i at Mānoa.

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Thank you to my advisor and dissertation chairperson, Steve: you have been both indulgent and encouraging of every single one of my “flights of fancy”, and I respect your support, mentorship and guidance greatly, more than words could ever express. Mahalo also to my other patient committee members, Liza: for the wonderfully enlightening design talks and chats, and for all the contemplative questions that arose as a result; Andy: for being able to always see my research potential and skills; and David: for your enthusiasm and confidence in helping me further my topics of interest.

Thank you to my friends and family here on the islands and back home: your constant and unwavering support has been so important to my growth, as a person and a student. All of the memories will forever be in my heart and cherished, truly.

DEDICATION

To my parents, Pravs, Paati & Pannu.

*You are my **everything** and I love you all.*

Thank you, thank you, and thank you.

ABSTRACT

“Come forth into the light of things, Let Nature be your teacher.” ~ William Wordsworth

The focus of this dissertation research is to extend and increase an understanding of sustainable building envelope design strategies, with specific focus on transfer of light, air, and heat, within a tropical site setting/context. Biomimetic architecture is a process that is primarily driven by inspiration from natural systems and organisms.

Designs and patterns found in nature are often resolved at the “macro” as well as at the “micro/nano” molecular levels, which prompts further investigation into present-day advancements in material science and nanotechnological concepts. Nanotechnology is a way of looking closer at systems and material structures and properties; the translation from biomimetic architecture to the nano-molecular scale of materials thus promotes sustainability in buildings, by providing ways and means to incorporate new technologies and novel material systems into the architectural design of building facades, that will further aid with the successful implementation of passive design strategies, in order to establish comfortable interior lighting, ventilation, and thermal conditions. Extensive literature reviews and material research are utilized for the bio-to-nano design process and analyses. Performance of design modules created has been tested using design simulations and reiterative analysis processes.

“Taking cues from Nature – creation of responsive (environment and human responsive) architecture” – is the idea that is the primary motivation behind the research focus. The key goal of this research is to propose alternative futures in building envelope design, for a site in Honolulu, which would serve as a digital prototype for similar such investigations into integrating nature-inspired macro and nanotechnology structures and materials into building systems design. Psychophysiology (the mind-body-interaction) and experimental testing is used as part of the final testing and analysis, to assess people’s responses to nature-inspired design and emerging building technologies.

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PART 1

Introduction and Background

1.1 Introduction

Research Query

How can we employ biomimicry (nature-inspired concepts) at the macro and micro/nano molecular scales (latter with nanotechnologies), in order to maximize THERMAL COMFORT, and create a more RESPONSIVE, DYNAMIC building envelope in the tropics? Furthermore, how can these spaces be better envisioned keeping in mind people's psychophysiological responses to the physical environment?

Doctorate Project Statement

With rapidly increasing urban populations across the globe and increased stress on the earth's biocapacity and energy/water reserves, it is important to reexamine the relationships between human beings and their surroundings. Particular emphasis is needed to bring in more efficient systems and drivers of maximizing the sustainable output within the built environment, and coexistence and symbiosis with the natural world are especially relevant to maintaining a healthy and sustainable built environment. Biomimicry and nanotechnology have recently come to light as new fields of inspiration for architectural design, providing specific insights into solving multiple building material and systems issues, and at different scales.

1.2 Goals and Objectives

Overarching Dissertation Goal

Creation of architectural prototypes that are responsive to the environment and to humans by utilizing effective strategies derived from organisms found in similar contexts in Nature.

The work of this dissertation will test the hypothesis that sites and buildings, designed incorporating: Biomorphic, Biomimetic, and Biophilic strategies, will serve to function more effectively as relevant examples of a responsive, dynamic built environment, and act as impetus for incorporating similar strategies in everyday architectural design. The intent of the associated design project is to also extend existing research in psychophysiology, by focusing on human visual cognition of landscapes and urban environments. If architects and urban planners could find out more about why certain settings or elements sustain calmness and evoke pleasure in

humans, this will enable them to construct and pattern environments that are more conducive to making healthier designs possible. Evidence-based design, substantial information and results based on quantitative and statistical data obtained by means of experimental research will also aid policy makers at the local, State, and National level in making decisions about creation, implementation, and maintenance of urban spaces in Honolulu as well as other similar contexts.

The principal goal of this dissertation research is to propose a primarily commercial design solution, for a site in Honolulu, which would serve as a digital prototype for further such investigations into integrating nature-inspired design strategies into building envelopes. The products of this dissertation exploration will serve as a foundation for similar site contexts where public responses to the urban environment will be critical to making community planning and design decisions.

Dissertation Objectives

- A.** Research strategies applicable from biomimicry into building envelope design for the site, with applications at the macro and nano-molecular scale.
- B.** Test/analyze the design applications for daylighting, natural ventilation, and thermal comfort within a proposed building/site in downtown Honolulu.
- C.** Determine people's responses to, and perceptions of, new technologies and design strategies in architectural façades using experimental research in psychophysiology.

The primary intent of this dissertation is to pursue new target goals; literally and figuratively “push the design envelope”, to define a new understanding for applying nature-inspired concepts in building envelope design.

- **BIOMORPHISM:** Application of the “design spiral”: Nature inspiration of the “leaf” within plant/tree systems to the building design modules.
- **BIOMIMICRY:** Propose new technologies and materials for implementation of the design modules, and test the performance of the design module configurations using simulations and graphic analyses.
- **BIOPHILIA:** Validate the design module typologies, by running experimental analyses using psychophysiology measures.

Design strategies incorporated within the building envelope will be run through a series of

analysis from beginning to end through the process:

- 1) Biomorphism: Scripting analysis to produce the design model configurations,
- 2) Biomimicry: Design simulations (daylight, ventilation, thermal), & Nanotechnologies
- 3) Biophilia: Experimental testing and analysis (psychophysiology: EEG, SCR, EEG, EMG)

1.3 Dissertation Contents and Layout

The dissertation layout and content hopes to establish a clear path of understanding ways to approach a multidisciplinary vantage point of designing with nature and natural systems.

Biomorphism, Biomimicry, and Biophilia are the three components discussed, studied, and analyzed, and reviewed in this dissertation: this defines the scope of the project. The author's focus is to follow a particular line of enquiry, namely: *What is the combined purpose of the three components (Biomorphism, Biomimicry, and Biophilia) in achieving design methodologies and implementation processes for sustainable design? How is sustainability redefined with the help of this dissertation, using these three components?*

The dissertation sets out to prove the following key principles to achieving a truly meaningful design that is deeply interconnected to humans and nature:

- 1) Design achieves dynamism,
- 2) Design contributes to homeostasis, and
- 3) Design effectively “reaches back to nature”

Part 1: Introduction

Provides an overview of the entire dissertation, including the following sections:

- 1.1 Introduction
- 1.2 Goals and Objectives
- 1.3 Dissertation Content and Layout
- 1.4 Background/Field of Study
- 1.5 Dissertation Hypotheses
- 1.6 Design Models

Part 2: Literature Review

Features the Literature Review, and further discusses in depth the literature sources and textual references that are apropos to the author's hypotheses.

2.1 Green Buildings: An Overview

2.2 Biomorphism: A Study

2.3 Biomimicry: A Study

2.4 Biophilia: A Study

Part 3: Methodology

Begins with the original work of the author, detailing the methods utilized for the analysis and implementation throughout the design process.

3.1 Eco Office: Site and Context

3.2 Eco Office: Design Program

3.3 Study Protocols and Methods

Part 4: Design Implementation and Analysis

Illustrates the implementation and analysis performed by the author, under the three sections: Biomorphism, Biomimicry (Materials and Processes), and Biophilia. Also, the results are finally concluded and discussed in detail.

4.1 Biomorphism: Analysis and Discussion

4.2 Biomimicry (Materials): Analysis and Discussion

4.3 Biomimicry (Processes): Analysis and Discussion

4.4 Biophilia: Analysis and Discussion

4.5 Results and Conclusion

Part 5: Bibliography

This last part of the document contains a list of references and texts that the author compiled during the research phases of this dissertation.

1.4 Background/Field of Study

1.4.1 INTRODUCTION

Peter Henri Bortoft (researcher and philosopher) suggests that a hermeneutic approach has the ability to uncover the wholeness of the thing studied:

“..we do not need the totality of the text in order to understand its meaning. We do not have the totality of the text when we read it, but only one bit after another. But we do not have to store up what is read until it is all collected together, whereupon we suddenly see the meaning all at once in an instant. On the contrary, the meaning of the text is discerned and disclosed with progressive immanence throughout the reading of the text.” (Bortoft, 2000, p. 284)

Bortoft places emphasis on the part to whole theory: this approach avoids the idea that while something can be dissected and perceived in separate pieces apart from one another; hermeneutics also values the totality of what is being studied.

Cities are increasingly in need of a design paradigm that uses technology and modern innovations effectively, and yet maintains a symbiotic relationship with the natural environment. Biophilia is a term that indicates “love of nature, of living organisms”. Biomimetic architecture is quickly developing as the instigating factor for responsive and eco-friendly designs.

The ideal style of architectural “zenith”, defined by sustainable design professionals, is achieved by creating spaces as defined by the relationship between *indoor and outdoor spaces*. Therefore, tropical areas have a unique, form-giving role in any settlement in that they offer a wide range of possibilities and avenues for creative exploration, without the constraints of extreme climatic fluctuations.

The tropical belt – where large areas of South East Asia, India, Africa, and parts of both North and South America are located – forms the biggest landmass in the world and has one of the highest numbers of rapidly developing cities.

The reasons for choosing the tropics as the dissertation project setting are as follows:

- A. Over 40% of the world’s population lives within 100 miles of coastlines.
- B. Hawaiian Islands consist of roughly 1.3 million people, with 74% of the population living in Honolulu, making the city a dense urban center.

- C. Architecture can be designed to be more responsive to environment.
- D. Potential of building's interaction with nature is easily achieved within this climate zone.
- E. This is due to the comfortable outdoor temperature range, and the natural scenic beauty of the landscapes/sites within the area.
- F. One of the few places where the boundaries between the exterior and the interior are minimal and easily blended.

PROBLEM STATEMENT: Due to increasing stress on the Earth's natural resources and limited biocapacity reserves, there is an urgent and imperative need to address the future energy crises, particularly within the Hawaiian Islands, to produce a richly sustainable future.

1.4.2 THE “ECO” ASPECT

How can sustainability effectively incorporate ideas and concepts for a healthier, greener future?

The objectives of this dissertation focus on the multidisciplinary nature of creating successful, highly efficient building design. The following points illustrate these connections:

- A. Symbiotic relationships exist between nature and technology/science, and between science and architecture.
- B. Recent (2008-2010) advancements in nanotechnology have created implications for architectural advancements.
- C. Green technology can be further developed with introduction of new materials, novel functions, etc., while minimizing net impact on natural resources.
- D. So, this generates a connection between Biomimicry and Nanotechnology, as the two in combination relate to architectural and systems design.

1.4.3 BIOMIMICRY: NATURE AND ARCHITECTURAL DESIGN

Some general aspects of biomimetic science:

- A. NATURE AS MODEL: Biomimicry is a new science studying nature by imitating or taking inspiration from existing design models and processes (Fig.1). This can help solve human problems, e.g., a solar cell inspired by a leaf.

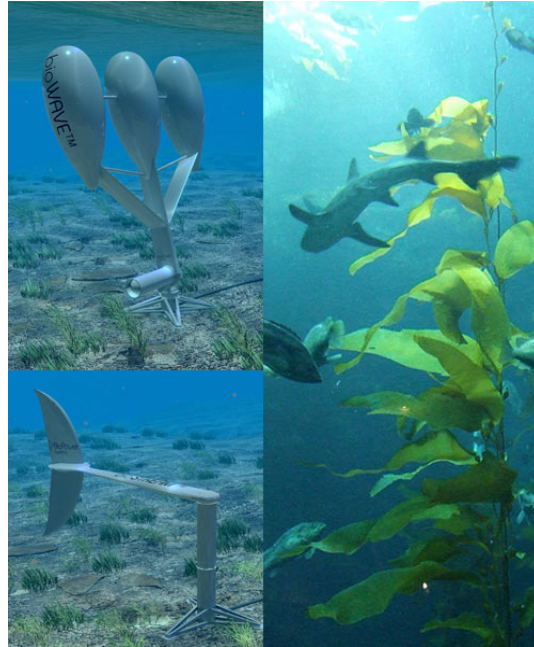


Figure 1: Sea Plant Movements = Underwater Turbines¹

- B. NATURE AS MEASURE: Biomimicry uses an ecological standard to judge the “rightness” of our innovations. (Fig 2). After 3.8 billion years of evolution, nature has learned:
- a. What WORKS.
 - b. What is APPROPRIATE.
 - c. What LASTS.

¹ Image Courtesy: http://www.flickr.com/photos/alexander_johmann



Figure 2: Natural Mussel Adhesive = Soy-based, Formaldehyde-free Technology²

- C. NATURE AS MENTOR: Biomimicry is a new way of viewing and valuing nature by introducing an era based on not what can be *extracted*, but what we can *learn* from nature.

1.4.4 BIOMIMICRY: NANOTECHNOLOGY AND ARCHITECTURAL DESIGN

Through the last few decades, there has been a rapid rise in technological advancement: ones that, both literally and figuratively, connect the architecture to the environment.¹ Modernism and contemporary architecture, and site-sensitive place making do not have to be mutually exclusive², as they have been in the past. It is the intent of the researcher, through this dissertation, to explore if the nature building relationships exist in the urban area chosen for the study within Honolulu and to understand the acceptance and visual cognition of such a space. The goal with creating a digital design prototype is to ultimately create responsive environments in urban areas within the tropics. This study will also help clearly define and classify the various design permutations that exist by effectively integrating biomimetics and technological innovations.

² Image Courtesy: www.treehugger.com/galleries/2009/08

¹ William H. Whyte, *The Social Life of Small Urban Spaces*. Project for Public Spaces, 1980, 34.

² Ibid, 37.

Nanotechnology is a field that explores material and system science at molecular levels, leading to new methods, systems, and properties previously undiscovered. Buildings and urban spaces are increasingly in need of detailed research and the incorporation of emerging technologies to create comfortable, livable, as well as inspiring architectural spaces. The idea behind implementing green design technologies for a tropical setting is to address the issue of thermal comfort, natural daylighting, and passive ventilation, to implement environmentally-responsive building façades and envelopes.

Although nanotechnology and the realm of nanoscience are not new, chemists will tell that they have been doing nanoscience for hundreds of years. Stained-glass windows found in medieval churches contain different-size gold nanoparticles incorporated into the glass — the specific size of the particles creating orange, purple, red, or greenish colors. Einstein, as part of his doctoral dissertation, calculated the size of a sugar molecule as one nanometer. Loosely considered, both the medieval glass workers and Einstein were nanoscientists.

However, there have been new approaches to developing applied technology — and the emergence of the right tools for the job. In fact, a committee *was* formed in the USA (the National Nanotechnology Initiative) and the following defining features of nanotechnology were posited:³

- A. Nanotechnology involves research and technology development at the 1nm-100nm ranges.
- B. Nanotechnology creates and uses structures that have novel properties due to their small size.
- C. Nanotechnology builds on the ability to control or manipulate at the atomic scale.

Seminal studies that characterize and dissect material properties have been performed at the nano-scale. Although this analysis might seem inconsequential to influence large-scale material properties, it might well play an important part in defining the architectural capabilities at the macro level, and thus becoming a key player in the way architects typify and depict different *a priori* categories of spaces and environments.

3 William H. Whyte, *The Social Life of Small Urban Spaces*. Project for Public Spaces, 28.

1.4.5 BIOPHILIA: PSYCHOPHYSIOLOGY AND ARCHITECTURAL DESIGN

The goal of this dissertation is to find ways to create environmentally responsive architecture. So how can we learn from human responses to the environment? People react differently to designs and ideas, and these differing views are supported or brought about by various factors—familiarity, cultural background, genetic makeup (instinctual responses), etc.⁴ One of the purposes of this research project is to employ the methodology of visual perception and cognition to see how and why people respond the way they do to urban spaces and the elements within them.

Evolutionary settings and systematic paradigms have been transferred over to urban settings for similar cognitive studies on environmental perceptions. Two other studies, based on the Kaplans' research, defined spatial configurations in terms of cognitive processes: *Coherence, Complexity, Legibility, and Mystery*.⁵ In later years and research, these simplified definitions were further expanded to include ratings based on *Spaciousness, Refuge, Enclosure, Coherence, Legibility, Complexity, Mystery, and Typicality*.⁶ The Kaplans also propose two cognitive processes that determine responses to environmental settings: Understanding and Exploration. They propose that first, the viewer has to recognize and be able to identify with the visual stimuli, and second, the respondents will have to attach themselves to the landscape or urban setting depicted in the picture, and should want to hypothetically explore beyond the confines of the image.

The objective behind the researcher's attention to the “ECO” aspect is to investigate and create a digital design prototype that would enable designers to create enriching spaces that will not merely prove functional, but also evoke and arouse positive emotional responses in humans.

Ontological Basis for Research

The ontological basis for this research is that there are some specific nature-based architectural cues that can be incorporated in building technologies, and that certain spatial configurations and patterns within the built environment do evoke more positive emotional responses in users of such spaces or areas than others; these positive emotions can be traced back to particular characteristics and design elements within the aforementioned spaces.

4 Rachel Kaplan, Stephen Kaplan, Robert L. Ryan, *With People in Mind: Design and Management of Everyday Nature*. Island Press, 1998.

5 Roger S. Ulrich, “Natural versus Urban Scenes: Some Psychophysiological Effects”. *Environment and Behavior* 13:5 (1981) 523-56.

6 Thomas R. Herzog, “A Cognitive Analysis of Preference for Urban Spaces”. *Journal of Environmental Psychology* 12 (1992): 237-48.

If we can delineate these particular elements, then they could be designed, through a combination of interactive design concepts and incorporation of effectively designed elements to create responsive concepts in architectural sustainability.

Epistemological Basis for Research

The epistemological basis for the dissertation project is to rely on information accrued from research, case studies, and from experimental data, as well as qualitative findings and correlation studies—these studies will be based on interactions between the researcher and the respondent(s) to understand and define the nature of relationships between natural systems and the built environment. So, rather than shy away from technological concepts while defining eco-friendly architectural concepts, the purpose of this dissertation is to effectively integrate biomimetic architecture with nanotechnology, to achieve a sustainable blend of the two, for a site within the tropics. There are numerous questions that any architect would ask when confronted by a new building technology such as this. How will this building method aid in designing better buildings? What alternatives will it provide? What are its potentials and limitations? What defines its character? How will this molecular growth process express itself?⁷ The applications of the nanotechnology in architecture can vary widely from early stages of design to the final touches of finishes and throughout the building's lifetime. Applications range from controllable adhesion and grip, switchable magnetism or light absorption, insulation materials for buildings that provide similar levels of insulation as conventional insulation materials, however, at a tenth of the material thickness.⁸

There is, however, a need for architects, scientists and technologies to give careful thought to specific ethical, cultural, architectural and environmental issues raised by nanotechnology, and to determine whether any new regulatory controls are required, and to enter into an open dialogue with the public.⁹ Studies on environmental aesthetics and cognition aid in making decisions at the planning policy level and help in controlling environments and therefore, human behavior.¹⁰

7 George Elvin, *The Nano Revolution: A science that works on the molecular scale is set to transform the way we build*. The Architect Magazine. (August, 2008). Accessed 1-11-2011, URL: <http://www.architectmagazine.com/industrynews.asp?sectionID=1006&articleID=492836&artnum=2>.

8 Sylvia Leydecker, *Nano Materials: in Architecture, Interior Architecture and Design*, Birkhäuser Architecture, 2008, 16.

9 Christopher J. Bosso, *Governing Uncertainty: Environmental Regulation in the Age of Nanotechnology*, RFF Press, 2010.

10 Roger S. Ulrich, "Natural versus Urban Scenes: Some Psychophysiological Effects". *Environment and Behavior* 13:5 (1981) 523-56.

1.5 Dissertation Hypotheses

The overarching purpose of the dissertation is based on a need to define the characteristics of the built environment as defined by total energy and water balance, built on concepts from biomimicry and nanotechnology. Subtropical sites are characterized by a comfortable band of temperature and humidity levels, and possess the ability to form highly energy-efficient spaces. Studies over the years describe various design concepts and characteristics of organisms and natural environments, and it is one of the goals of this research to delineate similar basic patterns and even define specific design elements in the context of building systems, specifically tropical architecture.

The goal of this dissertation is to find ways to create environmentally responsive architecture. The hypothesis of this research is that there are some specific nature-based architectural cues that can be incorporated in building technologies. If we can delineate these particular elements, then they could be designed, through a combination of interactive design concepts and incorporation of effectively designed elements to create responsive concepts in architectural sustainability. This will enable architects and urban designers to construct and mold environments that are more conducive to making healthier designs possible.

It is a wonder that although substantial exploration has been made along similar lines of inquiry, little actual research has been done on design elements driven by a combination of biomimicry and nanotechnology. Substantial information and results, based on information from research and testing data, will also aid policy makers at the local, State, and National level in making decisions about creation, implementation, and maintenance of green buildings in Honolulu as well as other similar contexts.

Some objectives of this study are to: -

1. Delineate and characterize specific strategies and materials derived from biomimetic and nanotechnology research, and correlate them to match specific design elements, characteristics, and patterns, within the tropical context.
2. Identify and recognize the energy efficiency tested and observed, with the building site in Honolulu.
3. Propose a design prototype and a corresponding framework for ideal office space: by utilizing Biomorphism, Biomimicry and Nanotechnology, and implementing Biophilic

design principles in the tropics.

4. Determine people's preferences to the architectural urban prototype in Honolulu.
5. Delineate and characterize differences in these responses and correlate them to match specific design elements, characteristics, and patterns within the designed spaces.

These objectives listed will, furthermore, help designers, planners, administrators, and educators in the field to accrue and develop new knowledge about current and future ecological design strategies and technologies, and understand the complexities between the built environment and people's perceptions.

1.6 DESIGN MODELS AND PRECEDENTS

1.6.1 Biomimicry Precedents

Following precedent studies illustrate some methods by which biomimetic strategies have been effectively applied in architectural design:

- A. EASTGATE CENTER (Zimbabwe)
- B. Lavasa Hill City (India)



Figure 3: Termite Den = Natural Ventilation Design¹¹

- A. EASTGATE CENTER: Designed, after the biomimetic model of a termite mound, to be ventilated and cooled by entirely natural means (Fig.3). Uses only 10% of the energy needed by a similar conventionally cooled building.
- B. LAVASA HILL-CITY: Rooftops will use native banyan fig leaf shape called a “drip-tip” (Fig.4) to allow water to run-off and clean the surface at the same time. The tiled shingle system (Fig.5) was created using the “Drip-tip” as a model to shed water.

¹¹ Image courtesy: [Alexander Johmann/Flickr: Wikipedia](#)



Figure 4: Leaf “Drip Tips”, Ficus Benghalensis (Banyan Tree)¹²

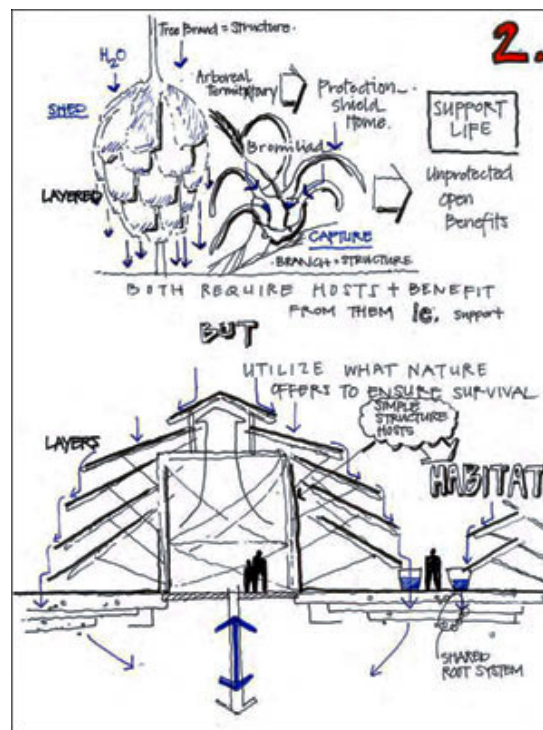


Figure 5: Drip Tips = Roof Shingles¹³

¹² Image courtesy: Google image searches.

¹³ Image courtesy: greensource.construction.com/news/080919biomimicry.asp

1.6.2 Nanotechnology Precedents

After some of the guidelines for the design have been laid out from biomimetic research, nanotechnology will be used as a tool, to tie the different approaches in with the functions of the amphibian/tree design strategies. Following precedent studies illustrate some methods by which nanotech strategies have been effectively applied in architectural design:

- A. NANO-HOUSE INITIATIVE: Collaboration between Australia's scientists, engineers, architects, designers and builders to design and build a new type of ultra-energy efficient house (Fig.6), with a focus to exploiting new materials being developed by nanotechnology.

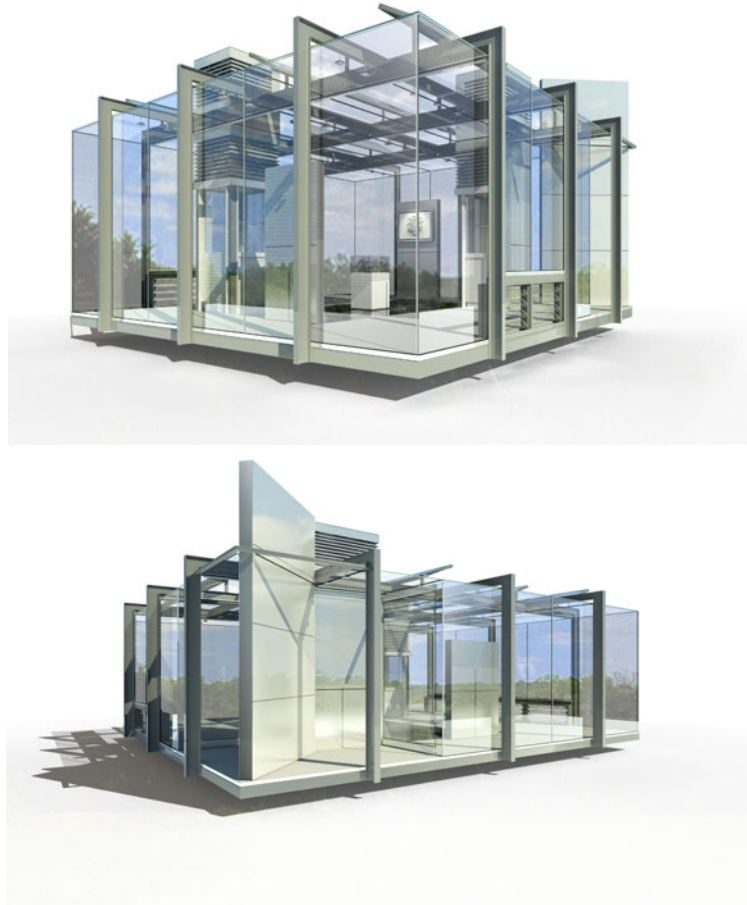


Figure 6: The Nano-House Initiative¹⁴

¹⁴ Image courtesy: www2.arch.uiuc.edu/elvin/nanohouse.htm

B. CARBON TOWER PROTOTYPE: 40-story mixed-use high-rise incorporating 5 innovative systems (Figs.7, 8):

- a. Pre-compressed double-helix primary structure,
- b. Tensile laminated composite floors,
- c. Two external filament-bound ramps,
- d. Breathable thin-film membrane,
- e. Virtual duct displacement ventilation.

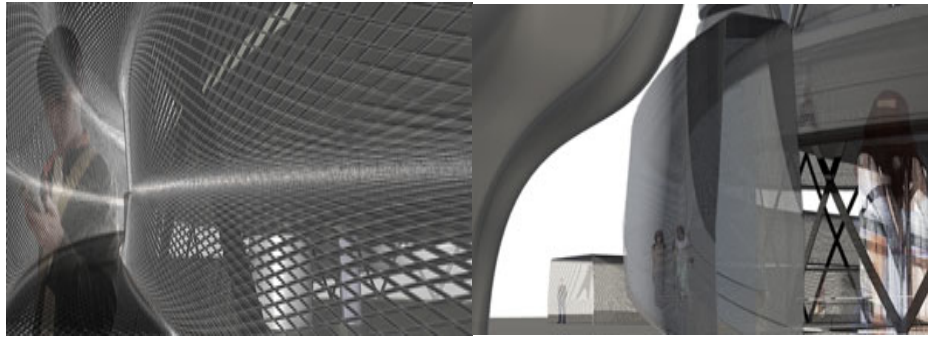


Figure 7: Carbon Tower Prototype: Renderings¹⁵

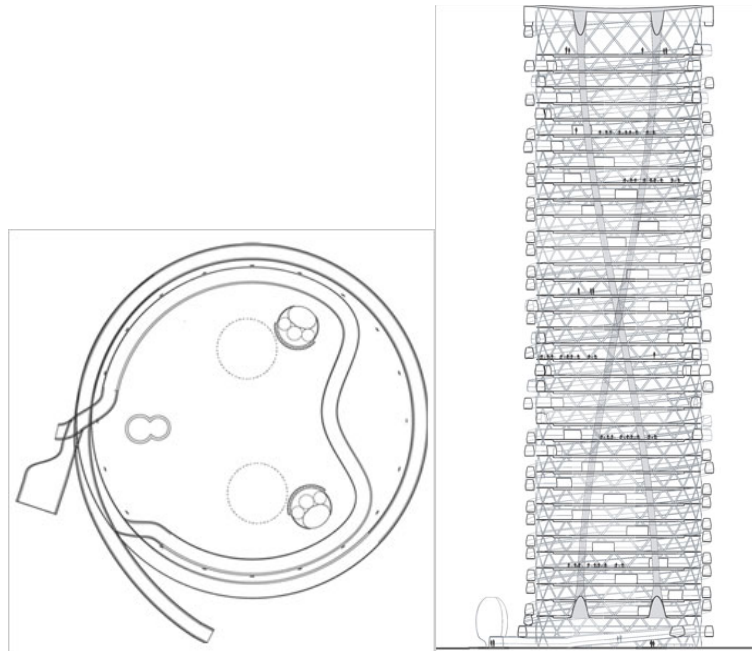


Figure 8: Carbon Tower Prototype: Schematics¹⁶

¹⁵ Image courtesy: www2.arch.uiuc.edu/elvin/carbontower.htm

1.6.3 LIVING BUILDING PRECEDENTS

Tyson Living Learning Center

Tyson (Eureka, Missouri) provides: a landscape-scale experimental venue for studies on ecosystem sustainability; an outdoor laboratory for important research and teaching opportunities from Washington University and other institutions; and research and educational opportunities for undergraduate and graduate students related to the environment and sustainability. (Figs. 9,10).



General Information

Location:	Eureka, MO, USA
Bioregion:	Heartland
Living Transect:	L3
Typology:	Building
Occupancy Type:	Education/Research
Project Area:	2,299 sqm / 24,751 sf
Building Area:	276 sqm / 2,968 sf
Start of Construction:	12/2008
Start of Occupancy Period	5/2009

Figure 9: Landscape and building tie in together to form sustainable living systems

The roof is covered in solar panels, rainwater runoff collected from the roof is processed in an adjacent rain garden, and all the materials were chosen to be healthy and sustainably sourced. “The concept of a living building set a higher bar for the university, as they wondered if this could be done here and what could they begin to accomplish on a larger scale,” says Daniel Hellmuth, a principal for Hellmuth+Bicknese and the project’s lead designer. “The Living Learning Center sparked that conversation, revealing the gap between 'medium green' and high-end sustainability, creating an exciting tension to push the limits of sustainable design.”¹⁷

¹⁶ Image courtesy: www2.arch.uiuc.edu/elvin/carbontower.htm

¹⁷ Sourced from: <http://www.eco-structure.com/education-projects/where-biology-meets-building.aspx>

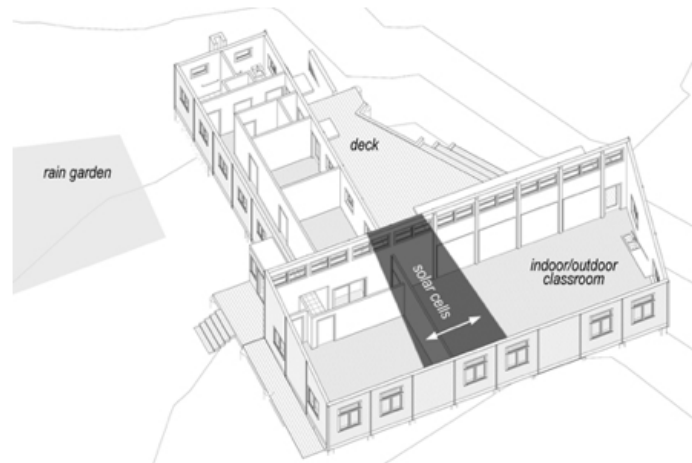


Figure 10: Aerial 3d-map of the Tyson Center

To achieve such a green, high-performance building, Hellmuth recommended benchmarking its design and construction against the Living Building Challenge (LBC), a set of rigorous standards created by the Cascadia Region Green Building Council. As per LBC's Version 1.3, the design focused on 16 prerequisites organized within six performance areas, or “petals”: site, energy, materials, water, indoor quality, and beauty & inspiration.

At the Living Learning Center, all regularly occupied spaces are designed to have direct views and daylight from windows; furthermore, every separate area provides for localized lighting, HVAC controls and operable windows to control outside airflow. Rainwater, collected from the roof and treated through particulate and UV bacterial filtration, supplies all water for the building. Composting toilets and a greywater system, as systems that have been put in place to add to the net-zero strategy kit, collect water from the building's sinks for use in irrigation on site. There is a careful use of recycled and salvaged materials (to help reduce net environmental negative impact), such as wood flooring and trim that was milled from trees already downed by storms, during previous occasions within this site. To meet its net-zero-energy target, the Center incorporated a 17.2kW photovoltaic (PV) array, utilizing 84 Evergreen ES-A 205W PV panels mounted on a unirac S-5 clip system and attached to the building's standing-seam metal roof.¹⁸

¹⁸ Sourced from: <http://www.eco-structure.com/education-projects/where-biology-meets-building.aspx>

The Omega Center for Sustainable Living

The Center for Sustainable Living Omega (Rhinebeck, New York), which serves as a wastewater filtration treatment facility, provides novel educational experiences that are almost spiritual and poetic in its architectural transition from the outdoor environment. The facility (Fig.11) is designed to reuse the treated wastewater for garden irrigation and in a greywater recovery system. Additionally, the system and building are taken in combination to serve a didactic purpose in educational program and ecological impacts on campuses.



Figure 11: Deck with natural, local wood materials and rock landscaping

PART 2

Literature Review

2.1 Green Buildings: An Overview

2.1.1 THE SUSTAINABILITY CHALLENGE

One of the first steps toward conception and creation of sustainable, nature responsive built environments is to carefully consider solutions for achieving maximum efficiency of systems present within the buildings. Unfortunately, there is still a large minority of builders (Fig.12) who will refuse to adopt green building practices until they are forced to by policy. The top down approach, therefore, focuses on ensuring that everyone adopts green policies, even those who otherwise would not want to adopt green policies and methods.

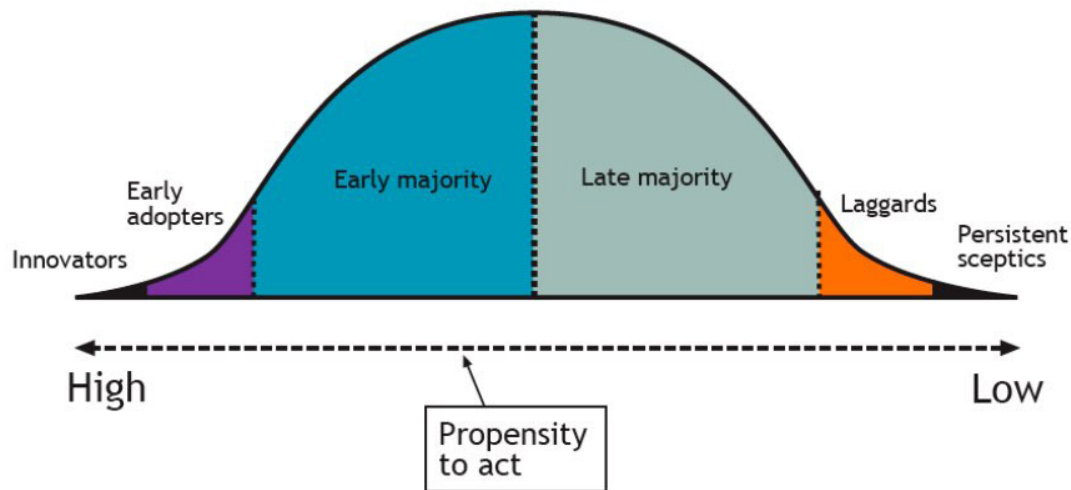


Figure 12: The Laggards¹⁹

“Laggards” are those who lag behind in the acceptance of new practices and methods in the green building industry. Everett Rogers first created this theory in his seminal work “Diffusion of Innovations”, which Malcolm Gladwell then popularized in “The Tipping Point”.

The 2030 Architecture Challenge focuses on relaying the message for immediate action in the field of green sustainability. Following points illustrate the urgency of the initiative behind the 2030 Architecture challenge.²⁰

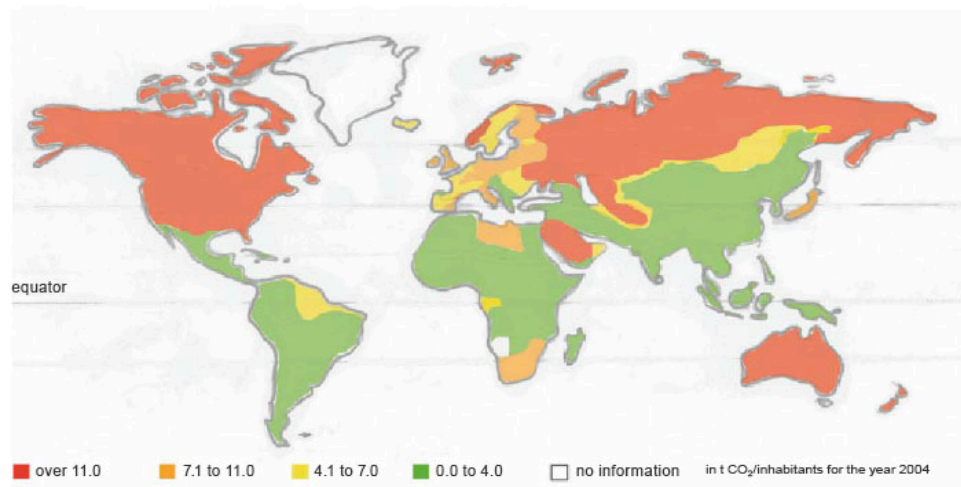
¹⁹ Diagram created based on Everett Rogers, *Diffusion of Innovations*, Glencoe - Free Press, 1962.

²⁰ 2030 Building Challenge Report, Accessed: http://pubs.giss.nasa.gov/docs/2010/2010_Kharecha_etal.pdf

“[1] Today, the Building Sector consumes about half of the energy produced in the U.S. each year, 68% of which is consumed in the form of electricity. About 48.5% of this electricity is produced by conventional coal-fired power plants. However, 81% of CO₂ emissions from electricity generation come from coal-fired power plants. The global climate problem becomes tractable only if CO₂ emissions from conventional coal use are phased out by the year 2030, and emissions from unconventional fossil fuels (e.g., oil shale and tar sands) are prohibited.

[2] Since most of these firms are multinational, the shift towards building to the 2030 Challenge carries important economic weight, representing a significant, stable global market for high-performance building materials, products, and on-site renewable energy systems.”²¹

As illustrated in Figs. 13 and 14 in the following pages, global consumption and depletion levels have begun to exceed available biocapacity. By the year 2050, it is estimated that the biocapacity reserve of the Earth will no longer be able to meet energy consumption.



*Figure 13: CO₂ Emissions Distribution levels per Capita, World Population, for the year 2004*²²

As depicted by the 2030 Architecture Challenge and guidelines, there is a need for immediate changes in design strategizing, lessening CO₂ footprint, and greening of new and existing buildings. Acceleration of global use of fossil fuel-rich materials, technologies, and design

21 2030 Building Challenge Report, Accessed: http://pubs.giss.nasa.gov/docs/2010/2010_Kharecha_etal.pdf

22 Michael Bauer, Peter Mösele, and Michael Schwarz, *Green Building – Guidebook for Sustainable Architecture*, Springer, 2007, 13.

methods has currently resulted in severe depletion of natural resources. Now is the time to take into account a multidisciplinary approach to designing and unraveling lifecycle processes of a building, so as to adapt human made environs to today's needs.

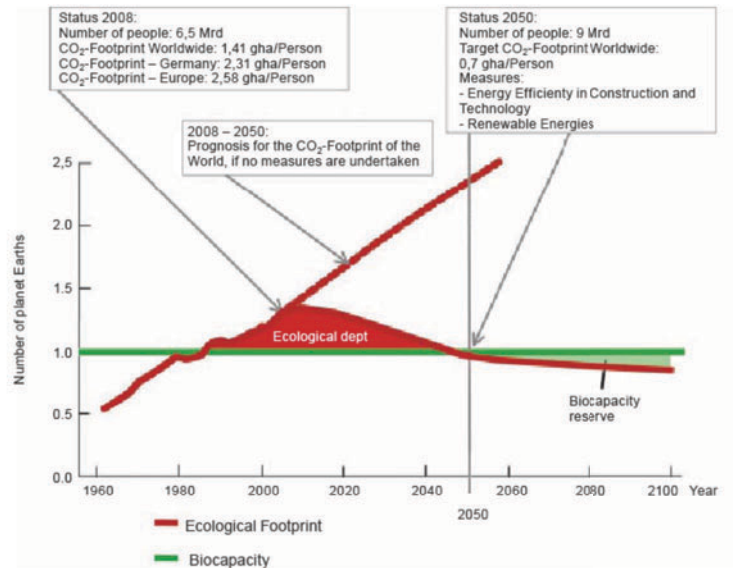


Figure 14: Sustainability wedges and an end to overshoot²³

The 2030 report prescribes some strategies for meeting the 2030 Challenge (Figs. 15 and 16): -

1. Design Strategies (Highest energy reductions achieved through implementation and design).
2. Technologies and Systems (Including on-site renewable energy systems).
3. Off-Site Renewable Energy (20% maximum).²⁴

Emphasis and a top-down approach should be placed heavily on renewable energy and closed-loop water management methods within buildings. On-site energy and water capture should be the norm, and “living buildings” serve to enhance the built environment and its ties to the natural one.

²³ Michael Bauer, Peter Möhle, and Michael Schwarz, *Green Building – Guidebook for Sustainable Architecture*, Springer, 2007, 14.

²⁴ 2030 Building Challenge Report, Accessed: http://pubs.giss.nasa.gov/docs/2010/2010_Kharecha_etal.pdf

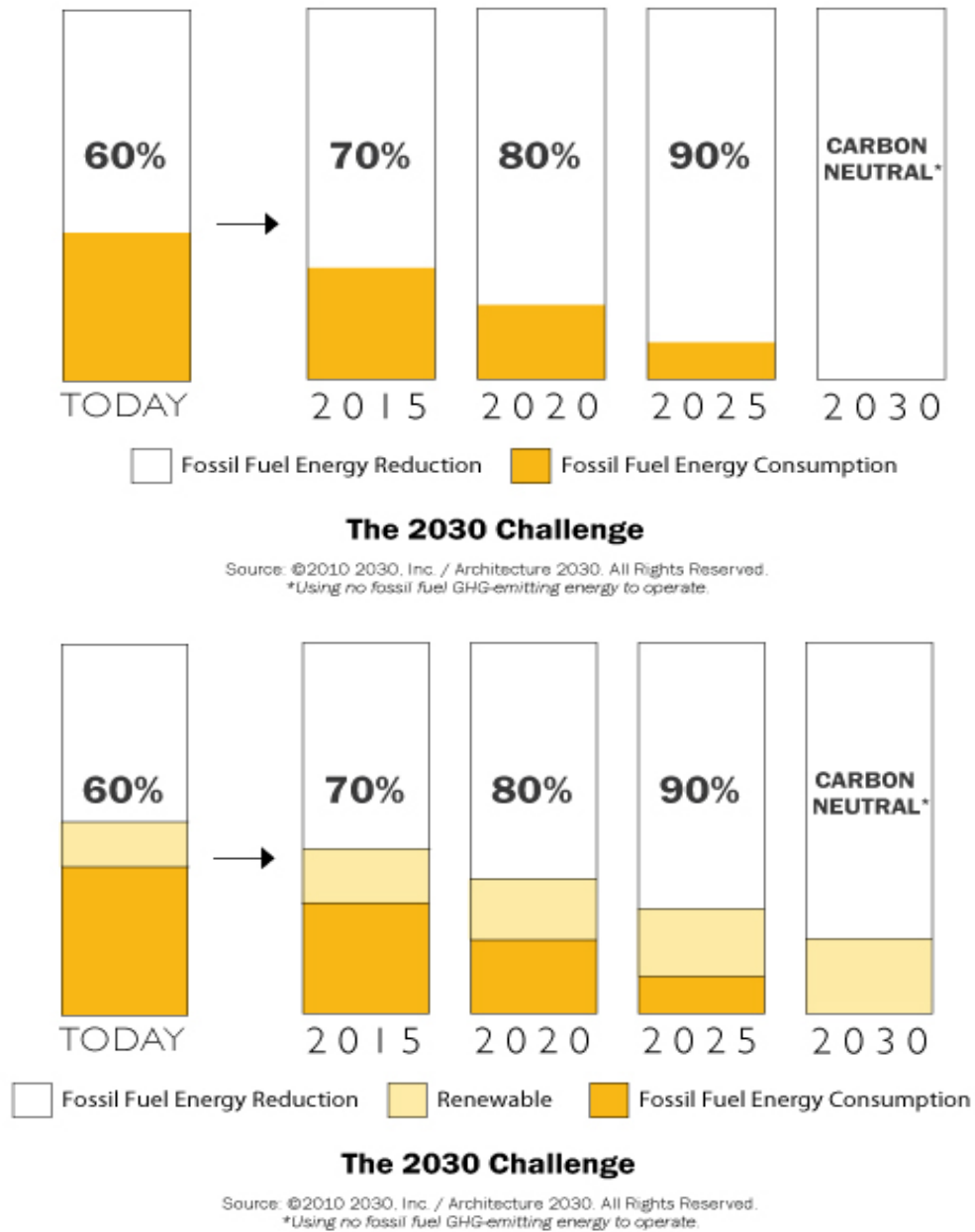


Figure 15: Fossil fuel consumption and future projections, 2030 Architecture²⁵

25 2030 Building Challenge Report, Accessed: http://pubs.giss.nasa.gov/docs/2010/2010_Kharecha_etal.pdf

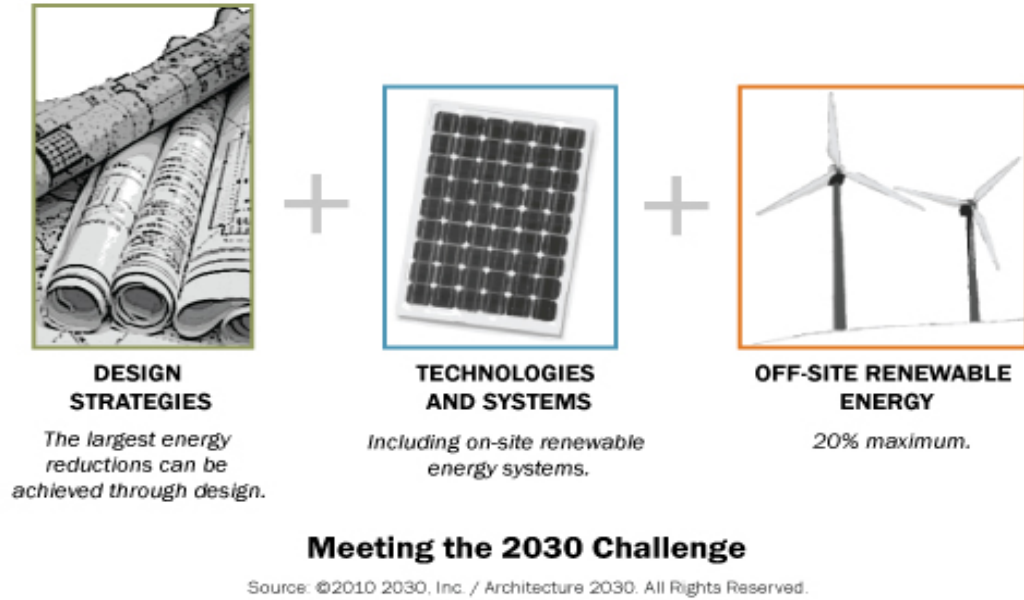


Figure 16: Meeting the 2030 Challenge (strategies that fit best)²⁶

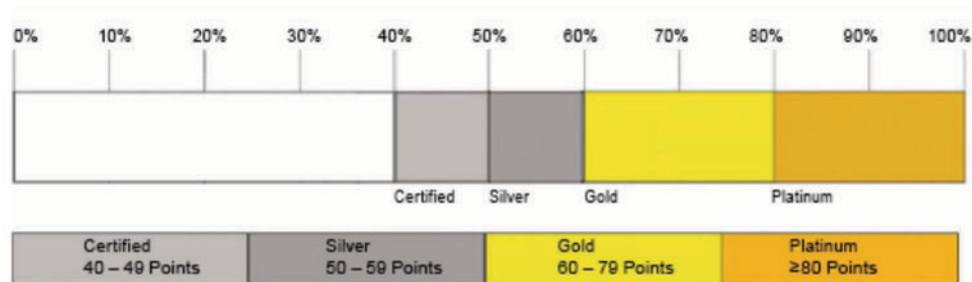


Figure 17: LEED Certification²⁷

LEED certification is one of the fastest growing and most widely adopted rating system for green buildings. Comparable to other worldwide standards, LEED focuses on nine areas of determination (Fig. 18).

Furthermore, a critical point worth noting is the weighting system within LEED, one that pays particular attention to “Energy and Atmosphere” and “Sustainable Sites” (Fig. 19).

²⁶ 2030 Building Challenge Report, Accessed: http://pubs.giss.nasa.gov/docs/2010/2010_Kharecha_etal.pdf

²⁷ Michael Bauer, Peter Mösle, and Michael Schwarz, *Green Building – Guidebook for Sustainable Architecture*, Springer, 2007, 15.



Figure 18: LEED Point Distributions²⁸

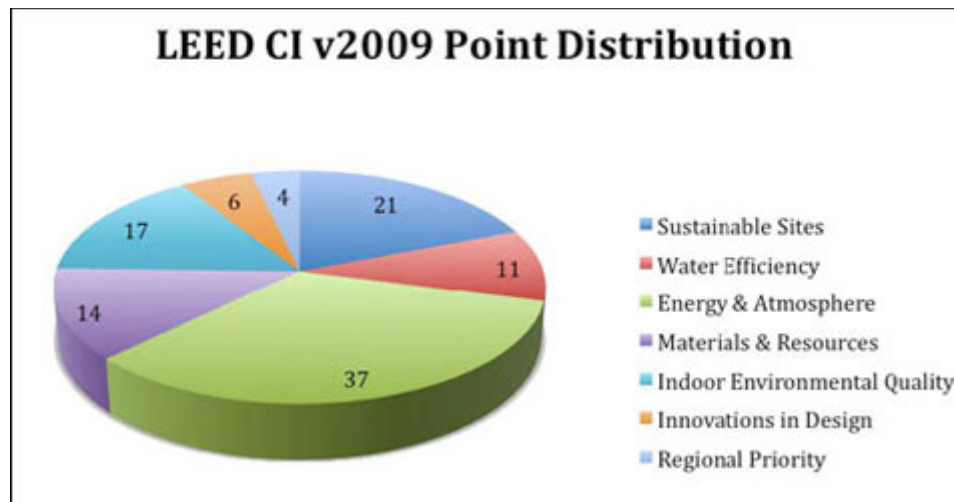


Figure 19: LEED Weighting²⁹

28 Image Courtesy: <http://www.usgbc-oklahoma.org/what-is-lead>

29 Image Courtesy: http://www.interiordesign.net/blog/Design_Green/34443-The_New_LEED_All_About_Weightings.php

The Living Building Challenge (LBC), a design list of prerequisites (petals), is prescribed by the USGBC (U.S. Green Building Council) - not intended to compete with the LEED ratings and standards in building design and construction, but to go above and beyond it. (Fig. 20). Sixteen (16) prerequisites are listed on the following pages, and illustrate the far-reaching capabilities of using this frame of reference from LBC.³⁰

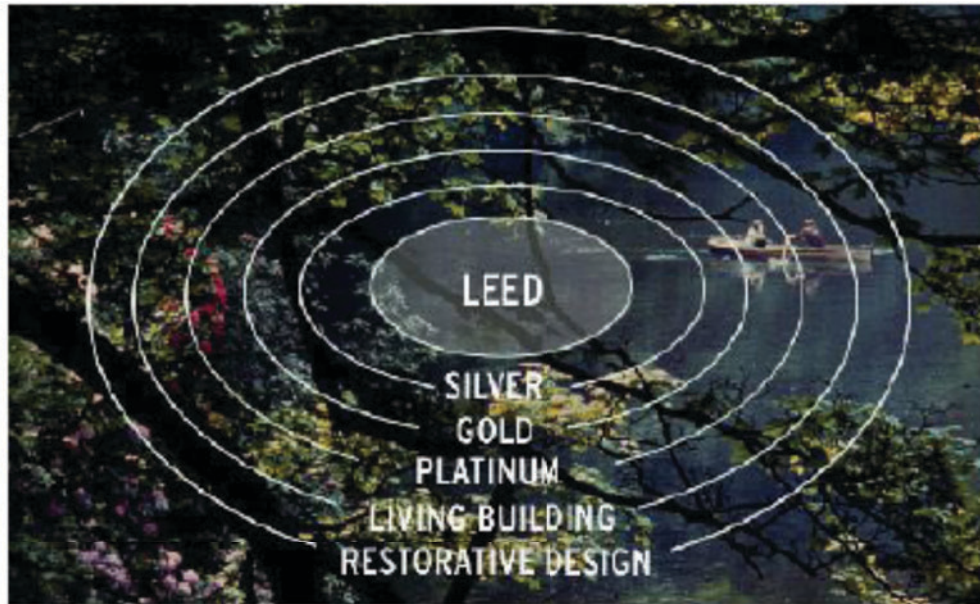


Figure 20: Concentric Rings to Sustainability.³¹

Living Building Challenge (LBC) Prerequisites:

Prerequisite One – Responsible Site Selection

You may not build on the following locations:

- On or adjacent to sensitive ecological habitats³ such as:
 - Wetlands⁴: maintain at least 50-feet, and up to 225-feet⁵ of separation
 - primary dunes⁶: maintain at least 120-feet of separation
 - old growth forest⁷: maintain at least 200-feet of separation
 - virgin prairie⁸: maintain at least 100-feet of separation
- Prime farmland⁹
- Within the 100 year flood plain¹⁰

³⁰ Michael Bauer, Peter Möslle, and Michael Schwarz, *Green Building – Guidebook for Sustainable Architecture*, Springer, 2007, 16.

³¹ Sourced from Living Building Challenge Webpages, Accessed at: <http://ilbi.org/lbc>

Prerequisite Two – Limits to Growth

Projects may only be built on greyfield or brownfield¹¹ sites that have been previously developed¹² prior to December 31, 2007. Project teams must document conditions prior to start of work.

Prerequisite Three – Habitat Exchange

For each acre of development, an equal amount of land must be set-aside for at least 100 years as part of a habitat exchange¹³.

Prerequisite Four – Net Zero Energy¹⁴

One hundred percent of the building's energy¹⁵ needs supplied by on-site renewable energy¹⁶ on a net annual basis.

Prerequisite Five – Materials Red List¹⁹

The project cannot contain any of the following Red List materials or chemicals.²⁰

- Cadmium
- Chlorinated Polyethylene and Chlorosulfonated Polyethylene²¹
- Chlorofluorocarbons (CFCs)
- Chloroprene (Neoprene)
- Formaldehyde (added)²²
- Halogenated Flame Retardants²³
- Hydrochlorofluorocarbons (HCFCs)
- Lead²⁴
- Mercury²⁵
- Petrochemical Fertilizers and Pesticides²⁶
- Phthalates
- Polyvinyl Chloride (PVC)²⁷
- Wood treatments containing Creosote, Arsenic or Pentachlorophenol

Prerequisite Six – Construction Carbon Footprint²⁸

The project must account for the embodied carbon footprint of its construction through a one-time²⁹ carbon offset tied to the building's square footage and general construction type.³⁰

Prerequisite Seven – Responsible Industry³¹

All wood must be certified by the Forest Stewardship Council (FSC),³² from salvaged sources, or the intentional harvest of timber onsite for the purpose of clearing the area for construction³³.

Prerequisite Eight – Appropriate Materials/Services Radius

Source locations for Materials and Services must adhere to the following restrictions³⁴:

Weight/Distance List

ZONE	MATERIAL OR SERVICE	MAXIMUM DISTANCE
7	Ideas	12,429.91 miles
6	Renewable Energy Technologies ³⁵	9000 miles
5	Assemblies that actively contribute to building performance once installed ³⁶	3000 miles
4	Consultant Travel ³⁷	1500 miles
3	Light, low density materials ³⁸	1000 miles
2	Medium Weight and density materials	500 miles
1	Heavy, high density materials ³⁹	250 miles

Prerequisite Nine Leadership in Construction Waste

Construction Waste must be diverted from landfills⁴⁰ to the following levels:

MATERIAL	MINIMUM Diverted/Weight
Metals	95%
Paper and Cardboard	95%
Soil, and biomass	100%
Rigid Foam, carpet & insulation	90%
All others - combined weighted average ⁴¹	80%
Asphalt	
Concrete and concrete masonry units (CMUs)	
Brick, tile and masonry materials	
Untreated lumber	
Plywood, oriented strand board (OSB) and particle board	
Gypsum wallboard scrap	
Glass	
Plumbing fixtures	
Windows	
Doors	
Cabinets	
Architectural fixtures	
Millwork, paneling and similar	
Electric fixtures, motors, switch gear and similar	
HVAC equipment, duct work, control systems, switches	

Hazardous materials in demolition waste, such as lead-based paint, asbestos, and polychlorinated biphenyls (PCBs), are exempt from percentage calculations.

Prerequisite Ten – Net Zero Water⁴²

100 percent of occupants' water use⁴³ must come from captured precipitation or closed loop water systems that account for downstream ecosystem impacts and that are appropriately purified without the use of chemicals⁴⁴.

Prerequisite Eleven – Sustainable Water Discharge

One hundred percent of storm water and building water discharge must be managed⁴⁵ on-site and integrated into a comprehensive system to feed the project's demands.

Prerequisite Twelve – A Civilized Environment

Every occupiable space must have operable windows⁴⁶ that provide access to fresh air and daylight⁴⁷.

Prerequisite Thirteen – Healthy Air: Source Control

All buildings must meet the following criteria:

- Entryways must have an external dirt track-in system and an internal one contained within a separate entry space.⁴⁸
- All kitchens, bathrooms, copy rooms, janitorial closets and chemical storage spaces must be separately ventilated.
- All interior finishes, paints and adhesives must comply with SCAQMD 2007/2008 standards⁴⁹. All other interior materials such as flooring and case works must comply with California Standard 01350 for IAQ emissions⁵⁰.
- The building must be a non-smoking facility.

Prerequisite Fourteen – Healthy Air: Ventilation

The building must be designed to deliver air change rates in compliance with California Title 24 requirements.

Prerequisite Fifteen – Beauty and Spirit

The project must contain design features intended solely for human delight and the celebration of culture, spirit and place appropriate to the function of the building.

Prerequisite Sixteen – Inspiration and Education

Educational materials about the performance and operation of the project must be provided to the public⁵¹ to share successful solutions and to motivate others to make change. Non-sensitive areas of the building must be open to the public at least one day per year, to facilitate direct contact with a Living Building.



Summary of Prerequisites

Number	Petal	Prerequisite
One	Site	Responsible Site Selection
Two	Site	Limits to Growth
Three	Site	Habitat Exchange
Four	Energy	Net Zero Energy
Five	Materials	Materials Red List
Six	Materials	Construction Carbon Footprint
Seven	Materials	Responsible Industry
Eight	Materials	Appropriate Materials/Services Radius
Nine	Materials	Leadership in Construction Waste
Ten	Water	Net Zero Water
Eleven	Water	Sustainable Water Discharge
Twelve	Indoor Quality	A Civilized Environment
Thirteen	Indoor Quality	Healthy Air: Source Control
Fourteen	Indoor Quality	Healthy Air: Ventilation
Fifteen	Beauty & Inspiration	Beauty and Spirit
Sixteen	Beauty & Inspiration	Inspiration and Education

To reiterate, the primary intent of this dissertation is to pursue new target goals, beyond the aforementioned prerequisites, to define a new understanding for applying nature-inspired concepts in building envelope design:

- BIOMORPHISM: Application of the “design spiral”
- BIOMIMICRY: Verify functions, Propose new technologies and materials
- BIOPHILIA: Experimental analyses using psychophysiology measures

Since the LBC prerequisites are **performance-based** and not **prescriptive based**,³² the design project from this dissertation - using visual simulations and analysis tools - will not necessarily replicate or reflect the final performance of the building accurately. Hence, design strategies incorporated within the design will be run through a series of analysis from beginning to end of

32 Sourced from Living Building Challenge Webpages, Accessed: <http://ilbi.org/lbc>

the process: Scripting analysis, Design simulations, Experimental testing and analysis.

A building's outer membrane, or envelope, regulates interactions between inner and outer environments, providing protection and comfort to contents and occupants. A building envelope's ability to regulate interactions with the environment affects structural integrity, indoor air quality, occupant comfort, health, and safety, energy efficiency, and durability.

Occupants and other living organisms within a built space require fresh air; yet, exfiltration and infiltration contribute to inefficient heating and cooling. Natural light contributes to health, safety, and productivity by improving visibility without the use of artificial energy sources. However, glare causes occupant discomfort. A certain amount of water vapor increases the comfort within a building, but excess moisture can peel paint, rot wooden frames, reduce the effectiveness of insulation, and lead to reductions in air quality. Furthermore, accumulations of water, snow, and ice can overload and collapse structures. An envelope's ability to retain and gain heat during the winter and prevent transfer during the summer influences the health and comfort of occupants as well as the building's total energy efficiency. Thus, a building's outer membrane contributes to safety and comfort by fulfilling four different sub-functions: regulate air transfer, regulate light exchange, regulate moisture transfer, and regulate heat transfer.

2.1.2 ENERGY EFFICIENCY IN BUILDINGS

To begin with an overview of energy applications and design strategies, it is important to first outline and define the perceived use of the space (Fig. 21), which will then determine the design of energy-efficient building concepts.

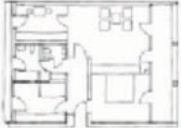
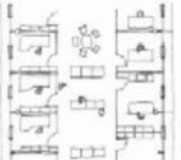

Application	Usage Means and Merit	Requirements	Need
 Living	Few people, Playing, Eating, Living, Cleaning, Watching Television, Hobbies, Parties	High level of thermal comfort, partially also sufficient if achieved per section (reading corner), different room temperatures (day/night), good air quality	Even thermal balance for radiation and convection, flexible system
 Office	Normal amount of people, concentrating on their work	High thermal comfort level, room temperature and humidity kept as comfortable as possible, temperature reduction at night for energy conservation reasons, fast heating-up at the start of operation, very good air quality	Even thermal balance for radiation and convection, flexible system, sufficient outdoor air supply, without draught
 School	Many people studying intensely, break, school operation	Very good air quality, high thermal comfort level covering all areas, short-term turn-off during break	High volume of outdoor air flow, short turn-off times, high level of performance reserves for heating-up process

Figure 21: Different user applications, according to their merits and requirements³³

In addition, temporal changes that might affect the design are also to be considered. For example, in office buildings, temperature regulators and consequent energy efficiency are affected only to the extent that the areas will aim for conservation of energy usage during nighttimes or after hours. Also, function determines the comfort levels required within the space, for instance, playing during the day such as in a kids' room might require a certain degree of warmth, while cooler temperatures are usually more preferred and desirable for sleeping during nighttime.

Temperature

Although several influences affect and influence the thermal comfort levels of people within the built environment (age, clothing type, health, etc.), there are also subjective measures that exist which help determine heat flows running through the person's body.

³³ Michael Bauer, Peter Möhle, and Michael Schwarz, *Green Building – Guidebook for Sustainable Architecture*, Springer, 2007, 25-26.

Factors	Conditions	
Internal surface temperature	Clothing	Nutrition
Air temperature	Degree of activity	Ethnic influences
Relative humidity	Individual control possibility	Age
Air movement	Adaptation and acclimatization	Sex
Air pressure	Day and annual rhythm	Bodily condition
Air quality	Room occupancy	Building design
Electromagnetic compatibility	Psycho-social factors	
Acoustic influences		
Visual influences		

Figure 22: Influence factors for comfort level sensation indoors³⁴

Infrared images of a person seen (Figs. 22 and 23) illustrate the heat indices during low levels of activity (left) and high-activity (right), with an outside air temperature of 26 deg. C (78 F). Uncomfortable levels of evaporation (sweating) can be seen as avoided within a temperature range of 26-34 deg.C (78-93 F).³⁵

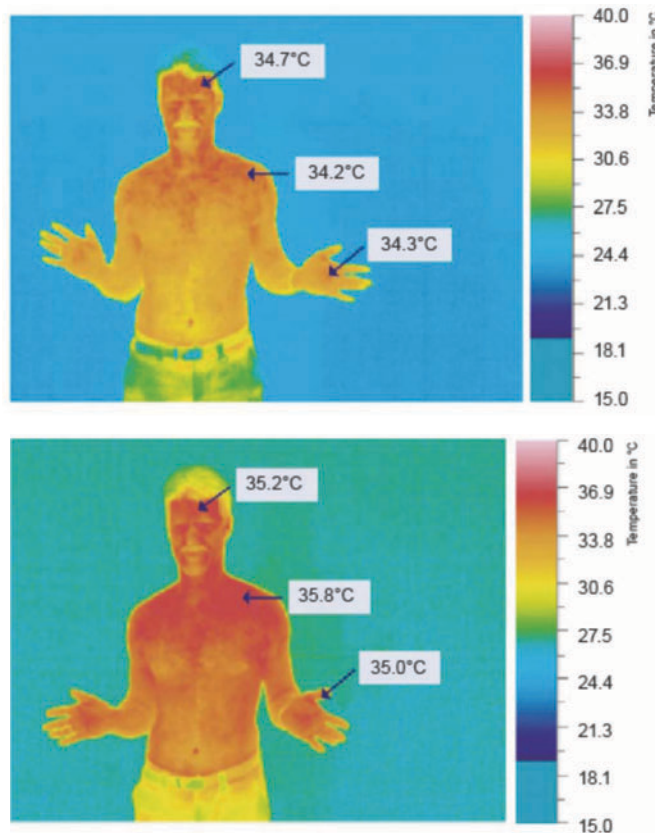


Figure 23: (T and B): Infrared images and physical activity

³⁴ Michael Bauer, Peter Mösele, and Michael Schwarz, *Green Building – Guidebook for Sustainable Architecture*, Springer, 2007, 26-28.

³⁵ Ibid, 27.

Comfortable indoor climate, performance levels, and work productivity are all directly related. In office buildings, specific deliberation should be agreed upon to achieving high indoor comfort levels, as it affects overall building financial gains.³⁶

It is clearly evident, as observed from Figs. 24 and 25, that performance levels in a person decline moderately at temperatures beyond 25-26 C (77-78 F); moreover, they lessen significantly at temperatures beyond 28-29 C (82-84 F).

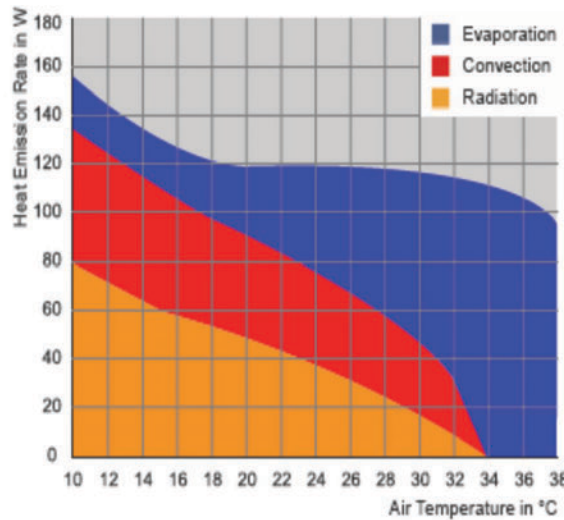


Figure 24: Heat emission rates for a person as it relates to ambient temperature³⁷

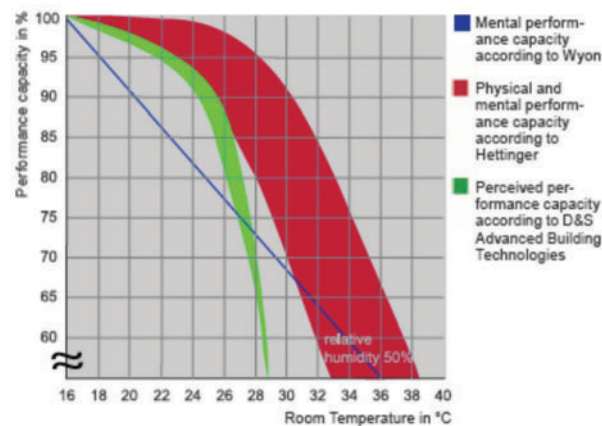


Figure 25: Performance capacity of a person as it relates to room temperature³⁸

36 ASHRAE, *ANSI/ASHRAE Standard 55R - Thermal Environmental Conditions for Human Occupancy*, Atlanta, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., 2010.

37 Michael Bauer, Peter Mösele, and Michael Schwarz, *Green Building – Guidebook for Sustainable Architecture*, Springer, 2007, 28.

38 Ibid, 28.

Humidity

Relative humidity plays another important role in influencing comfort levels within a space. When an environment does not experience high levels of humidity, it is not always necessary to induce dehumidification processes. However, if there are substantially long periods of time in a year during which the humidity levels are 35-40% or above, then it becomes crucial to dehumidify the ambient air before introducing it into the designed space.³⁹ (Fig. 26).

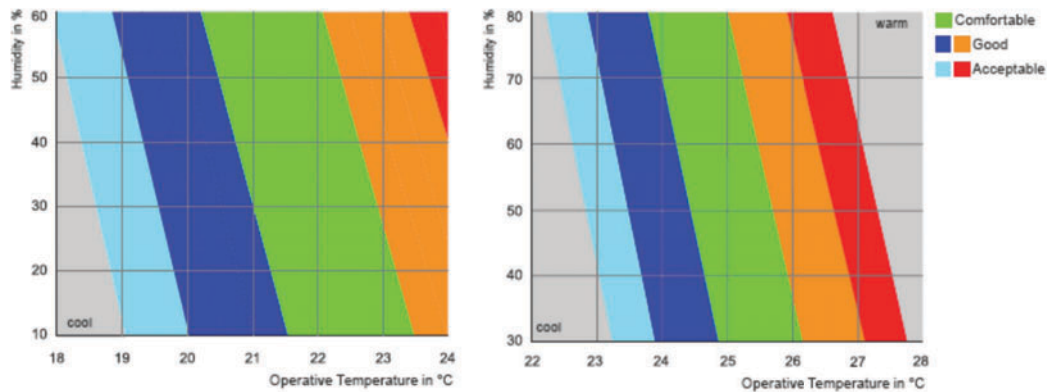


Figure 26: Relative humidity influence on operative indoor air temperature in winter (left) and summer (right)⁴⁰

This regulation of outside air by energy-intensive processes of dehumidification through cooling are not highly recommended; however, the use of absorbent-materials for dehumidifying the air, in a climate such as in Hawaii, for instance, will serve not only to diminish energy use but also reduce the carbon footprint and CO₂ levels.

³⁹ Ibid, 28.

⁴⁰ Michael Bauer, Peter Mösle, and Michael Schwarz, *Green Building – Guidebook for Sustainable Architecture*, Springer, 2007, 28.

Comfort Conditions

The following criteria have been developed by ASHRAE (American Society of Heating, Refrigerating, and Air Conditioning Engineers) to set a thermal comfort standard for interior environmental conditions. Criteria are described for three different environmental classifications, based on the approach used for space conditioning. These criteria will be further refined to address the particular nature of the Hawaiian climate, for the design site in Honolulu. For the purposes of this thesis, the first two methods (Natural Ventilation and Mixed Mode – combination of natural and mechanical ventilation) will be discussed.

Spaces that are Conditioned Solely by Natural Ventilation

Interior spaces shall meet the Adaptive Comfort criteria as outlined in ASHRAE Standard 55-2010 (Section 5.3).⁴¹ The basic concept of adaptive comfort is that the comfort zone, or range of acceptable indoor temperatures, drifts upwards in warm weather and downwards in cooler weather, particularly in environments where occupants have a variety of adaptive opportunities at their disposal. Adaptive comfort is not applicable to environments where occupants are detached from the thermoregulation of the space such as in centrally air-conditioned, sealed façade, office spaces. But for naturally ventilated buildings in which occupants have access to operable windows, the adaptive comfort concept is particularly relevant.

In 2004 the American Society of Heating, Refrigerating and Air-Conditioning Engineers was the first standards organization to formally incorporate this adaptive comfort concept into a regulatory document, with the comfort chart depicted in Fig.18.

Fig.18 indicates the optimum indoor temperature as a linear function of mean monthly outdoor temperature, with two acceptable comfort zones straddling the optimum – 80% and 90% acceptability. The meaning of these percentages is as follows: -

“An indoor operative temperature falling within the 80% range should be regarded as acceptable or satisfactory to at least 80% of building occupants who are exposed to it, and the tighter 90% acceptable temperature range is likely to satisfy 90% of occupants. For the purposes of the

41 ASHRAE, *ANSI/ASHRAE Standard 55R - Thermal Environmental Conditions for Human Occupancy*, Atlanta, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., 2010.

current criteria we propose the 80% acceptable temperature range, the upper limit of which can be written as:

$$\text{Upper 80\% Acceptable Limit} = 0.31 t_{a(out)} + 21.3 \quad (^\circ\text{C})^{42}$$

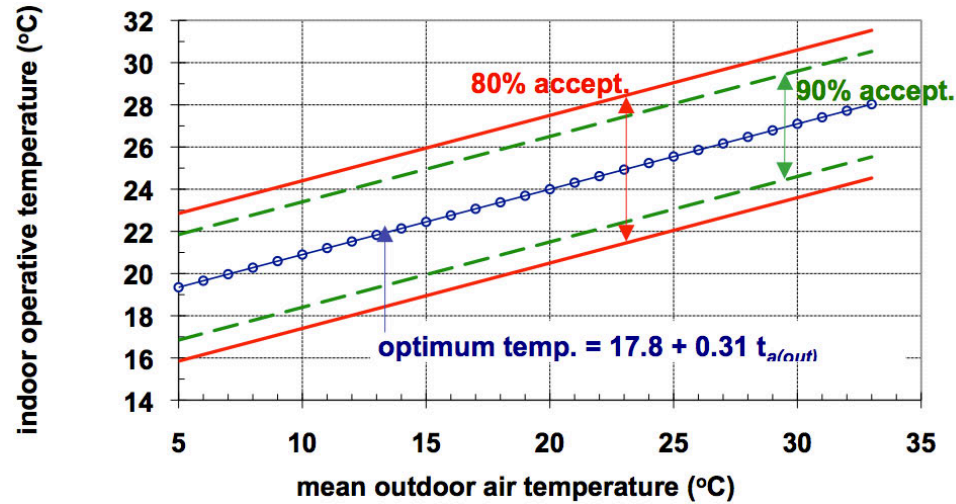


Figure 27: Adaptive comfort standard in naturally ventilated spaces

The ASHRAE 2010 adaptive comfort standard: $t_{a(out)}$ is simply an arithmetic average of the mean monthly minimum and maximum daily air temperatures for the month in question.⁴³

Elevated Air Speed

Figure 27 above includes the effects of people's indoor air speed adaptation in warm climates, up to 0.3 m/s (59 fpm) in operative temperatures warmer than 25°C (77 °F).⁴⁴ In naturally conditioned spaces, where mean air speeds within the occupied zone exceed 0.3 m/s (59 fpm), the upper acceptability temperature limits in Figure 27 can be increased by the corresponding Dt_o in Table 1 below. (These were calculated based on equal Standard Effective Temperature (SET) values as described in Section 5.2.3.2 of Standard 55-2010). For example, increasing mean air speed within the occupied zone from 0.3 m/s (59 fpm) to 0.6 m/s (118 fpm) escalates the upper acceptable temperature limits in Figure 27 by a Dt_o of 1.2°C (2.2°F). These adjustments to the upper acceptability temperature limits apply only at $t_o > 25^\circ\text{C}$ (77 °F) in which the occupants are

42 ASHRAE, *ANSI/ASHRAE Standard 55R - Thermal Environmental Conditions for Human Occupancy*, Atlanta, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., 2010.

43 Ibid.

44 Ibid.

engaged in near sedentary physical activity (with metabolic rates between 1.0 met and 1.3met).

Mean Air Speed (MAS)= 0.6 m/s	MAS = 0.9 m/s	MAS = 1.2 m/s
1.2°C (2.2°F)	1.8°C (3.2°F)	2.2°C (4.0°F)

Table 1: Operative Temperature vs. Mean Air Speeds

Table 1 indicates increases in Acceptable Operative Temperature Limits (Dt_o) in the Adaptive Comfort Standard (Figure 5.3) Resulting from Increasing Mean Air Speed Above 0.3 m/s (59 fpm).⁴⁵

Impact of Outdoor Humidity

The outdoor temperature that drives ASHRAE's adaptive comfort zone ($t_{a(out)}$) was defined pragmatically in Figure 16 as the mean monthly dry-bulb temperature simply because those climatic data are readily available for virtually every site across the globe. However, ASHRAE utilizes the Effective Temperature (ET). "ET" is defined as the temperature at 50% relative humidity that would cause the same sensible plus latent heat exchange from a person, as would the actual environment. This combines temperature and humidity into a single index, so two environments with the same ET should provide the same thermal response even though they have different temperatures and humidity, as long as they have the same air velocities. In the original model, the optimum indoor operative temperature is given as follows:

$$\text{Optimum indoor temperature} = 18.9^{\circ}\text{C} + 0.255 * (\text{outdoor mean ET})^{46}$$

Acceptable temperature ranges around the optimum in naturally ventilated buildings were specified as $\pm 3.5^{\circ}\text{C}$ for 80% general acceptability and $\pm 2.5^{\circ}\text{C}$ for 90% general acceptability, corresponding to the two acceptability deadbands shown in Figure 18.

⁴⁵ ASHRAE, *ANSI/ASHRAE Standard 55R - Thermal Environmental Conditions for Human Occupancy*, Atlanta, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., 2010.

⁴⁶ Ibid.

Spaces that are Conditioned by Either Natural Ventilation or Mechanical Space Conditioning (i.e. 'Mixed Mode')

Mixed-mode refers to a hybrid approach to space conditioning that uses a combination of natural ventilation from operable windows (either manually or automatically controlled) or other passive inlet vents, and mechanical systems that provide air distribution and some form of cooling. A well-designed mixed mode building allows spaces to be naturally ventilated during periods of the day or year when it is feasible or desirable, and uses air-conditioning for supplemental cooling when natural ventilation is not sufficient. The importance of the goal is to provide acceptable comfort while minimizing the significant energy use and operating costs of air conditioning.

At first glance, the assessment of thermal comfort in a mixed-mode building requires the evaluation of three different operating regimes.

- A. Occupied hours when spaces are conditioned solely by natural ventilation.*
- B. Occupied hours when spaces are conditioned by mechanical conditioning only.*
- C. Occupied hours that fall within an hour or two of the transition from one mode of space conditioning to the other.⁴⁷*

There is no agreement in either the research or professional communities about how to best define the thermal comfort operating conditions for mixed mode buildings in any of these regimes. There does seem to be agreement, however, that the chosen approach requires considered discussion between the design team and the building owners (and/or managers for the occupants, if different), as well as eventual occupant education about the building operation and the occupants' role in managing their own thermal environments (if appropriate). In all of these approaches, there need to be decisions about the extent to which you want to control (i.e., limit) or educate occupants about how to use the windows. These can be through automated windows, window locks, or red/green light signalling systems. In any of these approaches, whether or not people will find the PMV-based (conventional systems) or adaptive-based (natural ventilation) comfort zone acceptable has a lot to do with how the building is designed, and how it is operated throughout the year.

⁴⁷ ASHRAE, *ANSI/ASHRAE Standard 55R - Thermal Environmental Conditions for Human Occupancy*, Atlanta, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., 2010.

Conceptually, there is a continuum of strategies for how to approach this:

Conventional / conservative approach

Operate the building year-round to meet conventional set points (i.e., PMV-based comfort zone), no differently than as if it was a sealed building. Operable windows are seen merely as an amenity, and at best function like an economizer cycle. This approach may be appropriate if it is expected that mechanical cooling will be in operation for most of the warm season, occupants have minimal access to windows, and natural ventilation mode is expected for only a very short period of time.

Conventional / relaxed approach

Again use the conventional, PMV-based comfort zone. Use a slightly relaxed deadband from the conventional set points (i.e., 4°F) while heating/cooling equipment is operating. During times when the windows are open, expand the heating and cooling set points by an additional 2°F in each direction. So in this example, a conventional deadband of 70°F (heating) to 74°F (cooling) would be expanded to 68°F to 76°F.⁴⁸ This is a compromise that allows for improved energy efficiency, while still allowing for relatively quick recovery when the equipment turns on.

Adaptive / ramped approach

During periods when the spaces are conditioned solely by natural ventilation, interior spaces shall meet the Adaptive Comfort criteria as outlined in ASHRAE Standard 55-2010 (Section 5.3). Assessment of thermal comfort would follow the same criteria described above in section (1). If windows are then sealed and mechanical cooling is operating (changeover mixed-mode approach), a transition period would maintain conditions at the top of the Adaptive Comfort criteria. If mechanical cooling has been operating for an extended period, conditions would then ramp down to the top of the conventional PMV-based comfort zone.

Adaptive / conserving approach

In this approach, the Adaptive Comfort criteria are consistently maintained through alternative operation scenarios. Natural ventilation is used exclusively as long as conditions are maintained

⁴⁸ ASHRAE, *ANSI/ASHRAE Standard 55R - Thermal Environmental Conditions for Human Occupancy*, Atlanta, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., 2010.

within the Adaptive Comfort limits as described above in section (1), and mechanical cooling is used only as needed to ensure the building temperature does not rise above the adaptive comfort maximum temperature. This is most appropriate if the building operates primarily as a naturally ventilated building during significant periods of the year, the occupants are well-educated about building performance, and they are willing to play an active role in managing their own thermal environment (i.e., there is sufficient adaptive opportunity so that expectations are relaxed as well).

The following list of factors that may influence the development of these criteria are provided below to initiate further thinking and discussion on the topic.

- Envelope design, % of windows that are operable
- Access to windows (and management attitude about occupant use of windows)
- % of windows that are manual vs. automatic control
- Occupant education about building operation
- Availability of other means of personal control; flexible dress code in the workplace
- Zoning of naturally ventilated vs. air-conditioned spaces

2.1.3 OTHER MEASURES

Other standards of sustainable ratings exist with various organizations and sustainable agencies that promote green building technologies. The Los Alamos Sustainable Design Guidebook (Fig.19) prescribes a set of strategies according to ratable performance criteria: Standard Practice, Better, and High Performance.

	Standard Practice ¹	Better	High Performance
Relationships of Interior Spaces	<input type="radio"/> No attention to daylight or energy issues	<input type="radio"/> Highly occupied spaces located near perimeter	<input type="radio"/> Highly occupied spaces on south and north sides, spaces grouped for optimal energy zone configuration
Siting the Building	<input type="radio"/> No attention to solar access or prevailing winds	<input type="radio"/> Site review for adequate solar access at fenestrations and solar collectors	<input type="radio"/> Site review includes attention to impact of the project on neighboring buildings, potential future threats to solar access
Building Orientation	<input type="radio"/> No attention to sun paths or wind directions	<input type="radio"/> Facades with most fenestrations oriented to the south and north	<input type="radio"/> Roof slopes oriented for solar collection
Massing	<input type="radio"/> No attention to energy or daylighting	<input type="radio"/> Building shape slightly elongated to increase perimeter zone for daylighting	<input type="radio"/> Elongated or finger-plan shape with most occupied spaces along north or south walls
Energy Simulations	<input type="radio"/> Only done to comply with DOE Order 430.2A Title II reporting requirements	<input type="radio"/> Used during design development to evaluate energy-related details	<input type="radio"/> Used throughout the design process to inform key decisions
Glazing Selection	<input type="radio"/> Double-glazed insulated units throughout, possibly tinted	<input type="radio"/> Low-solar-gain, low-e glazing used throughout	<input type="radio"/> Glazing U-value, visible transmittance, and solar heat gain coefficient optimized for each elevation and application
Daylighting	<input type="radio"/> Perimeter spaces receive some daylight through view glazing	<input type="radio"/> High windows, skylights, and increased perimeter extends the usefulness of the daylighting	<input type="radio"/> Light shelves, overhead glazing, and electric light integration designed using daylight design software and/or physical models to maximize daylighting and the resulting energy savings
Thermal Storage	<input type="radio"/> Not considered	<input type="radio"/> Some exposed mass provided in the building to moderate temperature swings	<input type="radio"/> Extensive exposed mass linked to night-flushing to reduce cooling loads
Natural Ventilation	<input type="radio"/> Not provided	<input type="radio"/> Operable windows enhance occupant satisfaction, but lack building control integration	<input type="radio"/> Operable windows linked to building control system for optimal energy benefits and occupant satisfaction. Building designed to maximize air flow patterns and stack effect.
Solar Electricity (PV)	<input type="radio"/> Not considered	<input type="radio"/> Building designed for future PV, including electrical conduit and power panel availability	<input type="radio"/> Building-integrated PV panels generate electricity and contribute architecturally

Figure 28: Performance Ratings for Green Design⁴⁹

49 Los Alamos National Laboratory Building Design Guide, accessed: <http://engstandards.lanl.gov/esm/architectural/Sustainable.pdf>

2.1.5 NET ZERO ENERGY USE

BUILDING ENERGY CONSUMPTION CHARACTERISTICS

The systems in buildings that will consume the most energy are, in descending order:

1. Heating and Ventilation
2. Lighting
3. Cooling and Ventilation
4. Domestic Hot Water⁵⁰

The amount of energy consumed in a given building depends upon climate, building construction, use and type of operation, control and efficiency of the mechanical and electrical equipment. Climate conditions generally are considered to be the most important of all conditions affecting energy consumption.

BUILDING LOADS

Energy consumption can be divided between two types of loads: **Weather-Dependent Load** and **Base-Load**. The weather dependent load is self-descriptive. It includes the heating, ventilating and air conditioning loads. (Fig. 23). Base-Load consists of systems that are not affected by weather or, if they are, just slightly. For example, the lighting load is affected very little by weather, unless you are somehow relying on natural daylight. Elevator load is not affected by weather, except to the extent that it may receive less use when fewer people come in due to extremely inclement conditions.

Btu is short for British Thermal Unit, which is the amount of heat needed to raise one pound of water 1 F. It is also equivalent to the energy produced by one kitchen match.

⁵⁰ Los Alamos National Laboratory Building Design Guide, accessed: <http://engstandards.lanl.gov/esm/architectural/Sustainable.pdf>

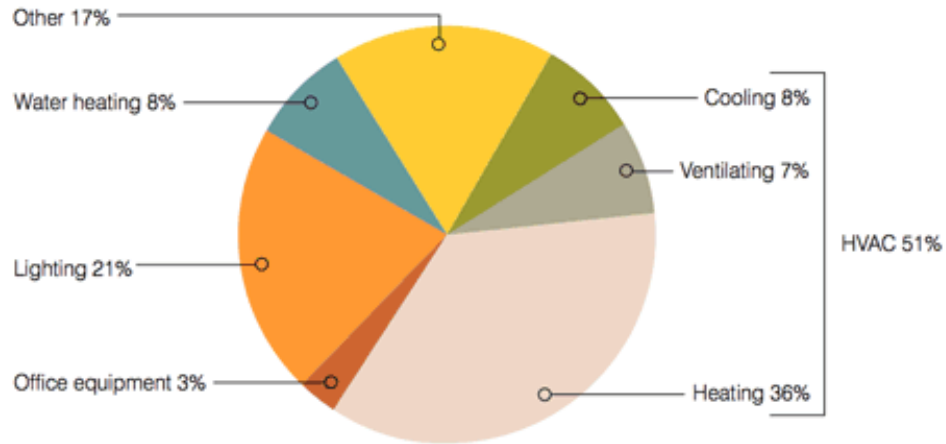


Figure 29: Typical commercial building energy usage⁵¹

DEGREE DAYS DEFINITION

Outdoor air temperature is a major climatic variable affecting energy use. The temperature is usually discussed in terms of “degree days” - heating degree days and cooling degree days. The number of heating degree days in a regular 24-hour day is determined as the difference between 65° F and the average of the high and low temperature for a specific day in question. For example, if the low temperature on a particular day is 35° F, and the high is 55° F, this day would have 20 heating degree-days derived as follows:

- High Temperature: 55° F
- Low Temperature: 35° F
- Average of High and Low $(55 + 35)/2 = 45°$ F

Heating Degree Days = 65° F - Average of high and low temperature = 65° F - 45° F = 20 degree days for that specific day.⁵² Adding all degree-days each day represents a total degree-day per year. Cooling degree-days are determined in a similar manner, except that 65° F is subtracted from the average.

⁵¹ Energy Information Administration, Commercial Buildings Energy Consumption Survey (CBECS): Major Fuel Consumption (BTU) by end use for all Buildings” September 2008. Accessible at:

http://www.eia.gov/emeu/cbecs/cbecs2003/detailed_tables_2003/detailed_tables_2003.html

⁵² Norbert Lechner, *Heating, Cooling, Lighting – Design Methods for Architects*, Wiley, 2001, 36-42.

2.2 BIOMORPHISM: A Study

2.2.1 BIOMORPHISM: NATURE AS MODEL AND MENTOR

The need for new metaphors in architecture is constantly evolving, as the metaphors are themselves: a reflection of the state of technological and design evolution within the particular region and time period. Natural inspirations: both biomimetic and biophilic design have been present in architectural history since the early eighteenth (18th) century.

Architects, designers and engineers have revisited their natural and biotic roots to investigate and seek out solutions to design and performance-based problems within architecture. The influential modernist architect, Le Corbusier, applied the machine as his metaphor in the 1930s. However, to solve today's tribulations and design in a manner more appropriate to nature, a new metaphor is needed. Benyus, in 1997, agreed by saying, "To emulate nature, our first challenge is to describe her in her terms."

Biomimicry does not seek to solely imitate or represent nature but endeavors to discover from nature. Janine M. Benyus conveys the idea that nature should be practiced and grasped in accordance with three strategic points: Nature as a Model, Nature as a Measure, and Nature as a Mentor. This dissertation will explore and finally express how, using Benyus' themes, it will be possible to arrive at nature-inspired formal characteristics of the building façade and module designs.

'Biomimicry [is] innovation inspired by nature. In a society accustomed to dominating or "improving" nature, this respectful imitation is a radically new approach, a revolution really. Unlike the Industrial Revolution, the Biomimicry Revolution introduces an era based not on what we can extract from nature, but on what we can learn from her.' ~Janine Beynus.

The term biomimetics, in every single one of its faceted variations (bionics, biomimicry, bioinspiration) has been in use since the 1950s when Otto Schmitt described it as "biology + technology" and applied it primarily within the field of engineering. In the field of architecture, however, this term has been adopted only within the last five to ten years and, too often erroneously, refers to studies limited to the imitation of the morphological characteristics of the biological realm. The foremost challenge facing the field of architecture nowadays goes beyond the basic quest of aesthetics towards a responsible attitude of the built environment for the future.

Biology and ecology are disciplines that can influence design projects in unexpected and interesting ways. How environmental and climatic conditions have influenced the evolution of behavioral and physiological traits of natural organisms and environments can inform and inspire fields such as design and architecture.

Biomimicry and its use of nature as a model, obtains inspiration from biology to solve human and architectural problems. As the science of biology expands and uncovers new species and novel theories about the way in which these organisms interact within their environments, so does the way in which architecture adapts and learns new approaches towards structure, tectonics and performance within a building.

Thus, biomimicry and nature as a model for architecture can be related to the ideology and processes occurring within nature that solve architectural problems. In other words, it is imperative, at this point in architectural history, to study different species to learn and interpret their operational and functional measures within their respective environments so that these lessons and measures can be applied to materials and systems that aid passive ecological design.

2.2.2 MORPHOLOGY, GEOMETRY, AND NATURE-INSPIRED DESIGNS

Natural elements that are found to be associated with aesthetic preference. *Morphology* is the word natural scientists use to describe form and structure in nature. Morphology can describe topographic features and geology or plants and animals. In the literature on landscape aesthetics, these elements are often referred to in terms of natural ‘contents’. Humans seem to display a consistent preference for four types of natural contents: savannas, water-features, vegetation, and flowers.⁵³ Importantly, the widespread aesthetic appeal of these elements is found to be suggestive of an inborn predisposition to like such natural elements.

Since appropriate emotional responses to these natural elements contributed to survival, one can apprehend how, even today these natural features elicit awareness and positive emotional states. For example, in interior spaces, such as offices, the presence of landscape features and plants is found to increase the aesthetic appeal and feeling of comfort of the setting.⁵⁴ Furthermore, when subjects are enquired to make a mandatory choice between an urban environment without vegetation, and a natural and vegetated setting or landscape, then the latter were discovered to be more preferred and aesthetically appealing.

Among vegetated landscapes and environments in urban settings, it was also found that those urban settings that also contain some vegetation (especially trees) or a water feature are preferred most.⁵⁵ Now, it is critical to note that this contrasts with modern or contemporary built environments in other ways. Upon comparison of vegetated landscapes and non-vegetated (human-made, urban) architectural settings, the latter most often involved images of quite modern buildings, or at the very least buildings that are not quite complex or ‘rich’ in form. Nevertheless, in the following chapters it will be pointed out that nature is often characterized by a typical sort of geometry (fractal or geometric with an organic quality), and for the most part rarely finds itself represented in modern buildings or modern urban settings. One needs to address and appreciate that the preference for vegetated scenes is not merely present because of the context of placing within a natural setting, but that it relates back to the fundamental geometrical characteristics of the place or setting. It is now important to begin ponder over the transitory challenges and

⁵³ R.S. Ulrich, Human responses to vegetation and landscapes. *Landscape and Urban Planning*, 1986, 13, 29-44.

⁵⁴ L. Larsen, Adams, J., Deal, B., Kweon, B.S. & Tyler, E., Plants in the Workplace. The Effects of Plant Density on Productivity, Attitudes, and Perceptions. *Environment and Behavior*, 1998, 30, 261-281.

⁵⁵ R.S. Ulrich, Human responses to vegetation and landscapes. *Landscape and Urban Planning*, 1986, 13, 29-44.

differentiations that exist among the “natural” versus the “built”; however, an even finer appreciation would be to distinguish those characteristics and resolve the underlying reasons or preference “settings” to which humans ultimately respond to.

One critical point of note (and that which supports the methodology in this dissertation) is that it is not always important to always important to experience the features of the natural world directly, in realistic experience. Studies and tests over time have also proved that positive emotional valence is achievable with the use of videos, realistic simulated images, or slides. Anecdotal findings and reports by Roger Ulrich and others have made clear this point of note, and may be utilized as an important representation of nature and natural forms.

Natural form might reveal the wholeness of nature and the person-environment relationship. There is a clear distinction between simply approaching from a reductivist *biomorphic* perspective of engaging the natural form versus a more thorough, holistic use-based, *biomimimetic* commitment to the idea and concepts behind these same natural forms.

Furthermore, another distinguishing characteristic of importance is *scale*. It is therefore said that regardless how seductive natural form can be, the result that is valid and most suggestive is the way by which humans experience the scaled-form in real space and context. The pure, and direct translated process of mimicking natural forms, disregards the wholeness of natural form through a rather callous distillation to the natural form for superficial application of characteristics, and thus not always possible to be identified as the type of work developed from true inspiration or emulation of the environmental complexity. Architects and designers will be able to achieve a more seamless and all-inclusive engagement with the natural world by considering the totality of form, ecosystem and process that have shaped the environment that is being considered. Thus, designers might better understand not only the wholeness of nature, but also the wholeness in nature, in people, and in the built environment.

2.23 BIOMORPHIC DYNAMISM AND PHENOMENOLOGY

Biomimicry and Biomorphism are often interrelated; several successful design ideas are “borrowed” from the adaptations and functional and formal characteristics found in nature, among the plant and animal species.

Phenomenological aspects of nature play an important role in the study of nature and form. During the 18th century, Johann Wolfgang von Goethe “devised a qualitative way of seeing and understanding that can rightly be called a phenomenology of the natural world”. In a series of studies of light that is perhaps the most easily understood example of his ability to move beyond conventional science’s study of nature, Goethe identifies the wholeness of what is studied along with parts reflecting the whole: he termed it *delicate empiricism*.

Goethe’s studies on color and light led to theories that reached beyond conventional vantage points that looked at nature as a static entity, that can be broken down and understood in parts. His studies posited for example, that darkness was not merely the “passive absence of light” but instead an interactive entity that changes and alters the qualitative aspects of light itself. He termed this reciprocity and interplay as the “ur-phenomenon”.

Ecologist Mark Riegner described an environment and its living forms to be interconnected, it was his contention that natural form serves as a hermeneutical approach for considering an environment that cannot speak for itself. One specific and didactic example used by Riegner to illustrate this approach is that of the bindweed leaf: its shape at the base of the plant nearest the darker-moister environment (adjacent to the soil) are simpler, more-rounded, and with fewer serrations (Fig.30). However, as the evolution of the leaf cross-section reaches and proceeds towards the tip of the plant, nearer the sun and where moisture is not as predominant, it is seen that the leaf shape is more complex, thinner, with numerous serrations.⁵⁶ Riegner discusses how this shift from simpler to more complex leaf form frequently occurs not only with individual plants but that the leaves of an entire ecosystems—e.g., a rainforest—can reflect this polarity of light/dry and dark/moist. At the same time, in other species such as the brittle bush of the Sonoran Desert, the leaf morphology is found to change seasonally with large, soft leaves in the rainy season, and smaller, hair-covered foliage in dry season.

⁵⁶ Mark Riegner, & Wilkes, J. Flowforms and the language of water. In D. Seamon, & A. Zajonc (Eds.), *Goethe's Way of Science: A Phenomenology of Nature* (pp. 233-252). Albany, N.Y.: State University of New York Press, 1998.



Figure 30: Drawing illustrating the transition from simple rounder leaves at the base (right), to more complex shapes towards the tip (left).⁵⁷

As will be explored in detail in the “Biophila” section of this dissertation, it has been proven, time and again, that the aesthetic attraction to nature and natural life forms is one of the strongest inclinations in the human species. There is this hardwired tendency, which is intrinsically biological, which has been primordially instrumental in promoting and elevating humans’ capacity for the following traits:

- 1) imagination
- 2) creativity
- 3) curiosity
- 4) problem solving
- 5) exploration

Nature has regularly inspired designs in the built environment; however, most of these examples are grounded in natural form. Although form is an obvious component of nature, Benyus and

⁵⁷ Mark Riegner, & Wilkes, J. Flowforms and the language of water. In D. Seamon, & A. Zajonc (Eds.), *Goethe's Way of Science: A Phenomenology of Nature* (pp. 233-252). Albany, N.Y.: State University of New York Press, 1998.

other scientists working with biomimicry warn that merely mimicking natural form misses the idea of biomimetic design. Benyus writes that “a full emulation of nature engages at least three levels of mimicry: form, process, and ecosystem”.⁵⁸ It can be appreciated that so many of the most recognized and widely renowned case studies of architecture and landscape architecture have occurred as a result of the “nurture nature” design process and implementation.

As will become clear in following chapters, this triad of form, ecosystem, and process lays the foundation for a comprehensive (qualitative and quantitative) interpretation and design implementation of Biomorphism, Biomimicry, and Biophilia.

⁵⁸ Janine Benyus. *Biomimicry: Innovation Inspired by Nature*. Harper Perennial. (2002), 48.

2.2.3 THE BIO-INSPIRATION “SPARK”: LEAF MORPHOLOGY

Biomorphism, in this dissertation, poses the following questions:

- A. What is the ideal shape? (FORM)
- B. How does the form evolve and change? (MORPHOLOGY)

For the initial design of the façade modules, the concept of a leaf as it relates to the tree (microcosm: macrocosm) was investigated.



Figure 31: Bio-inspiration: Leaf and Tree (microcosm: macrocosm)

Studies on leaf placement, position, and hierarchy within the tree’s longitudinal cross-section and latitudinal structure (cross canopy) revealed some interesting trends in leaf evolution:

- 1) “SUN” AND “SHADE” LEAF ARRANGEMENTS⁵⁹
 - a. Outer, exposed leaves in a canopy have a higher sinus/area ratio (=notched) than inner leaves (minimizes shading inner leaves to allow more light penetration).
 - b. Outer leaves are typically thicker (greater specific leaf weight) than inner leaves
 - c. Leaves in the shade have reduced thickness (less mesophyll)

⁵⁹ “Leaf morphology & light microenvironments: A field exercise.” Westmoreland, D (1989) *American Biology Teacher* **51**: 303 - 306

- d. Leaves in the sun have longer petioles than those in the shade (hold blade away from stem to reduce shading)

2) TOP AND BOTTOM LEAF ARRANGEMENTS⁶⁰

- a. Effective leaf size decreases with increasing light and elevation
- b. Leaf thickness decreases with increasing light and elevation

Sun leaves were found to be thicker, more elongated (to adjust for DIRECT SOLAR RADIATION, during specific time windows of sunlight penetration). Shade leaves were thinner, broader, more expanded (to adjust for DIFFUSE RADIATION, sunlight constant throughout the day). Top leaves were thicker, longer (to allow for greater WATER STRESS TOLERANCE), while bottom leaves measured were discovered to be wider, bigger, and of higher porosity (this to enable PHOTOSYNTHESIS activity within the leaf). These leaf arrangements were maintained so as to maintain an internal leaf temperature of 21deg.C. Studies by Helliker and others quantitatively measured the temperatures of tree canopies that exist in modern times; this study used the “oxygen isotope method” after temperature calculations, and then used this data to compare against the local weather station data. They hypothesized that, as the tree system they incorporated carbon from carbon dioxide (CO₂) into sugars, there was bound to be fluctuation of the internal leaf temperatures during the day, and that the isotope content of the tree rings should represent the average temperature of the leaves. Surprisingly enough, the results of the study data revealed a pattern: average leaf temperatures hovered around 21 °C, and this was consistently found to be true irrespective of the location of trees in climes ranging from very warm to cold.⁶¹

So what is happening in the leaf systems to cause this stability in temperatures? In general, plants have adapted in warm climates by utilizing ingenious, yet simple, morphological adjustments and tactics to adjust their temperature. Some trees or plants have been discovered to cool off by shifting the angle of their leaves relative to the sun, while others incorporate fine hairs as a kind of natural sunblock. Moreover, plants can also ‘sweat’, which thus helps them to sacrifice water in exchange for the cooling effects of evaporation.⁶² These findings corroborate those mentioned earlier in this section, where studies revealed patterns regarding leaf morphology and distribution.

⁶⁰ “Comparative studies of leaf form: Assessing the relative roles of selective pressures and phylogenetic constraints.” Givnish, TJ (1987) New Phytologist 106 (Suppl): 131 - 160.

⁶¹ Helliker, B. R. and Richter, S. L. *Nature* doi:10.1038/nature07031 (2008)

⁶² “Leaves keep their cool” accessed at <http://www.nature.com/news/2008/080611/full/news.2008.884.html>, 2011.

2.3 BIOMIMICRY: A Study

2.3.1 Biomimetics: Nature and Design

“In the future, the houses we live in and the offices we work in will be designed to function like living organisms, specifically adapted to place and able to draw all of their requirements for energy and water from the surrounding sun, wind and rain. The architecture of the future will draw inspiration, not from the machines of the 20th century, but from the beautiful flowers that grow in the landscape that surrounds them.”⁶³

There is an increasing interest in the study of biomimetic architecture as a means of understanding and further exploring the realm of responsive design. It is important for architects to know not only about the building's physical components, but also crucial to understand the impacts that the building materials and design strategies have on energy consumption. Design concepts that effectively incorporate natural daylighting and ventilation, and efficiently employ and use components and materials to regulate heating and cooling conditions within the buildings, are ultimately necessities in today's urban conditions of high density and over-consumption.

Buildings, should, and ought to be compared to living organisms in that they evolve in response to climate and topography, changing form and composition as necessary to protect what was inside from the elements, while regulating temperature and humidity to the greatest extent possible.

Just like the flora and fauna alter in evolutionary characteristics from biome to biome, so should any building as it responds and reacts, similar to a living organism, to the outside conditions and natural fluxes.⁶⁴ Amory Lovins, founder of the Rocky Mountain Institute reminds us that what we want is comfort not higher energy bills and oil spills. What is needed is a return to the old metaphor, one that respected regional differences and environmental health while embracing appropriate technologies than can give us the comfort, service and security we now expect.⁶⁵

63 Bob Berkebile and Jason McLennan. “The Living Building: Biomimicry in Architecture, Integrating Technology with Nature”. Accessed 1-5-2011, URL: http://jasonmclennan.com/draft/articles/The_Living_Building.pdf, 1-2.

64 Monique Blacha and Anne Bots. “Nature's Experiences for Building Technology”. Accessed 1-6-2011, URL: <http://www.arnopronk.com/bestanden/acapulco2%20def%20Arno%20Pronk.pdf>.

65 Corey Griffin. “An Introduction to Biophilia and the Built Environment”. Rocky Mountain Institute. (November 14, 2006). <http://www.rmi.org/sitepages/pid1079.php>

We are finding it useful to measure our designs and innovations against a test set forth in Benyus' Biomimicry, "Is there a precedent for this in nature?" If so the answers to the following questions will be yes:

- A. Does it run on sunlight?
- B. Does it use only the energy it needs?
- C. Does it fit form to function?
- D. Does it recycle everything?
- E. Does it reward cooperation?
- F. Does it bank on diversity?
- G. Does it utilize local expertise?
- H. Does it curb excess from within?
- I. Does it tap the power of limits?
- J. Is it Beautiful?⁶⁶

"Why biomimicry? Nature is a genius. To survive, nature needs to solve lots of problems. Evolutionary survival of the fittest makes animals, plants and microbes the real and perfect engineers. They have found what works, what is appropriate, and most important, what lasts here on Earth."⁶⁷ As Janine Benyus, co-founder of the Biomimicry Guild, mentions in her book '*Biomimicry: Innovation Inspired by Nature*', there are two approaches for using biomimicry: -

- a) In the **biology-to-design** approach, a biological phenomenon suggests a new way to solve a human design challenge.
- b) In the **design-to-biology** approach, the innovator starts with a human design challenge, identifies the core function, and then reviews how various organisms or ecosystems are achieving that function.

This dissertation section on Biomorphism reinterprets the first method, where plant systems and leaves are looked at closely with particular reference to daylighting, natural ventilation, and thermal comfort strategies. Such strategies are then related back to the built environment for

⁶⁶ Janine M. Benyus, *Biomimicry: Innovation Inspired by Nature*, Harper Perennial. 2002, 291.

⁶⁷ Monique Blacha and Anne Bots. "Nature's Experiences for Building Technology". Accessed 1-6-2011, URL: <http://www.arnopronk.com/bestanden/acapulco2%20def%20Arno%20Pronk.pdf>.

further review and application, under the sections of Biomimicry and Biophilia, for a site in Honolulu, Hawai'i.

“Challenge to Biology” Design Spiral (CBS) – This is a series of checkpoints and questions that serve as places through the process at which to pause and review and refine the biomimetic process of the design and research. (Fig 24).⁶⁸

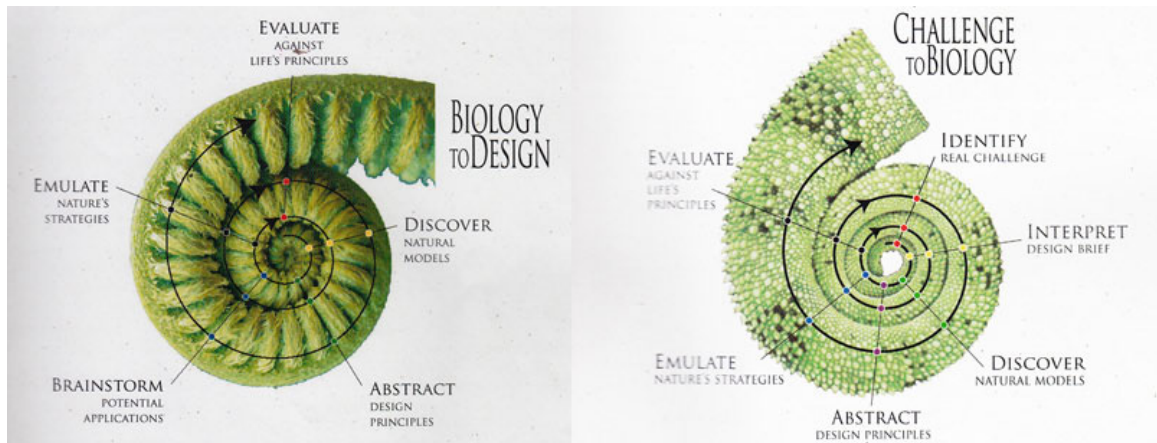


Figure 32: The “Challenge to Biology” Design Spiral⁶⁹

A. **Identify** - *Develop a Design Brief of the human need*

- Develop a Design Brief with specifics about the problem to be resolved
- Break down the Design Brief to identify the core of the problems and the design specifications
- Identify the function you want your design to accomplish: What do you want your design to do? (not “what do you want to design?”). Continue to ask why until you get to the bottom of the problem
- Define the specifics of the problem:
 - Target Market: who is involved with the problem and who will be involved with the solution?
 - Location: where is the problem, where will the solution be applied?

⁶⁸ Janine M. Benyus, *Biomimicry: Innovation Inspired by Nature*, Harper Perennial. 2002, 291.

⁶⁹ Design Spirals developed by the Biomimicry Institute, accessed at: <http://biomimicry.net/>

B. **Interpret** - *Biologize the question; ask the Design Brief from Nature's perspective*

- Translate the design function into functions carried out in nature. Ask, “How does Nature do this function?” “How does Nature NOT do this function?”
- Reframe questions with additional key words
- Define the Habitat/Location
 - Climate conditions
 - Nutrient conditions
 - Social conditions
 - Temporal conditions

C. **Discover** - *Look for the champions in nature who answer/resolve your challenges*

- Find the best Natural Models to answer your questions
- Consider Literal and Metaphorical
- Find champion adapters by asking, “Whose survival depends on this?”
- Find organisms that are most challenged by the problem you are trying to solve, but are unfazed by it
- Look to the extremes of the habitat
- Turn the problem inside out and on its head
- Open discussions with Biologists and specialists in the field

D. **Abstract** - *Find the repeating patterns and processes within nature that achieve success*

- Create taxonomy of life’s strategies
- Select the champions with the most relevant strategies to your particular design challenge
- Abstract from this list the repeating successes and principles that achieve this success

E. **Emulate** - *Develop ideas and solutions based on the natural models*

- Develop concepts and ideas that apply the lessons from your Natural teachers.
- Look into applying these lessons as deep as possible in your designs:
 - Mimicking Form
 - Find out details of the morphology
 - Understand scale effects

- Consider influencing factors on the effectiveness of the form for the organism
- Consider ways in which you might deepen the conversation to also mimic process and/or ecosystem
- Mimicking Function
 - Find out details of the biological process
 - Understand scale effects
 - Consider influencing factors on the effectiveness of the process for the organism
 - Consider ways in which you might deepen the conversation to also mimic the ecosystem
- Mimicking Ecosystem
 - Find out details of the biological process
 - Understand scale effects
 - Consider influencing factors on the effectiveness of the process for the organism

F. **Evaluate** - How do your ideas compare to principles of nature?

- Evaluate your design solution against nature
 - Build from the bottom up
 - Self-assemble
 - Optimize rather than maximize
 - Use free energy, cross-pollinate
 - Embrace diversity
 - Adapt and evolve
 - Use life-friendly materials and processes
 - Engage in symbiotic relationships
 - Enhance the bio-sphere
- Develop appropriate questions from Life's Principles and continue to question your solution
- Identify further ways to improve your design and develop new questions to explore. Questions may now be about the refinement of the concept:
 - Packaging, Manufacture, Marketing, Transport
 - New Products - additions, refinement

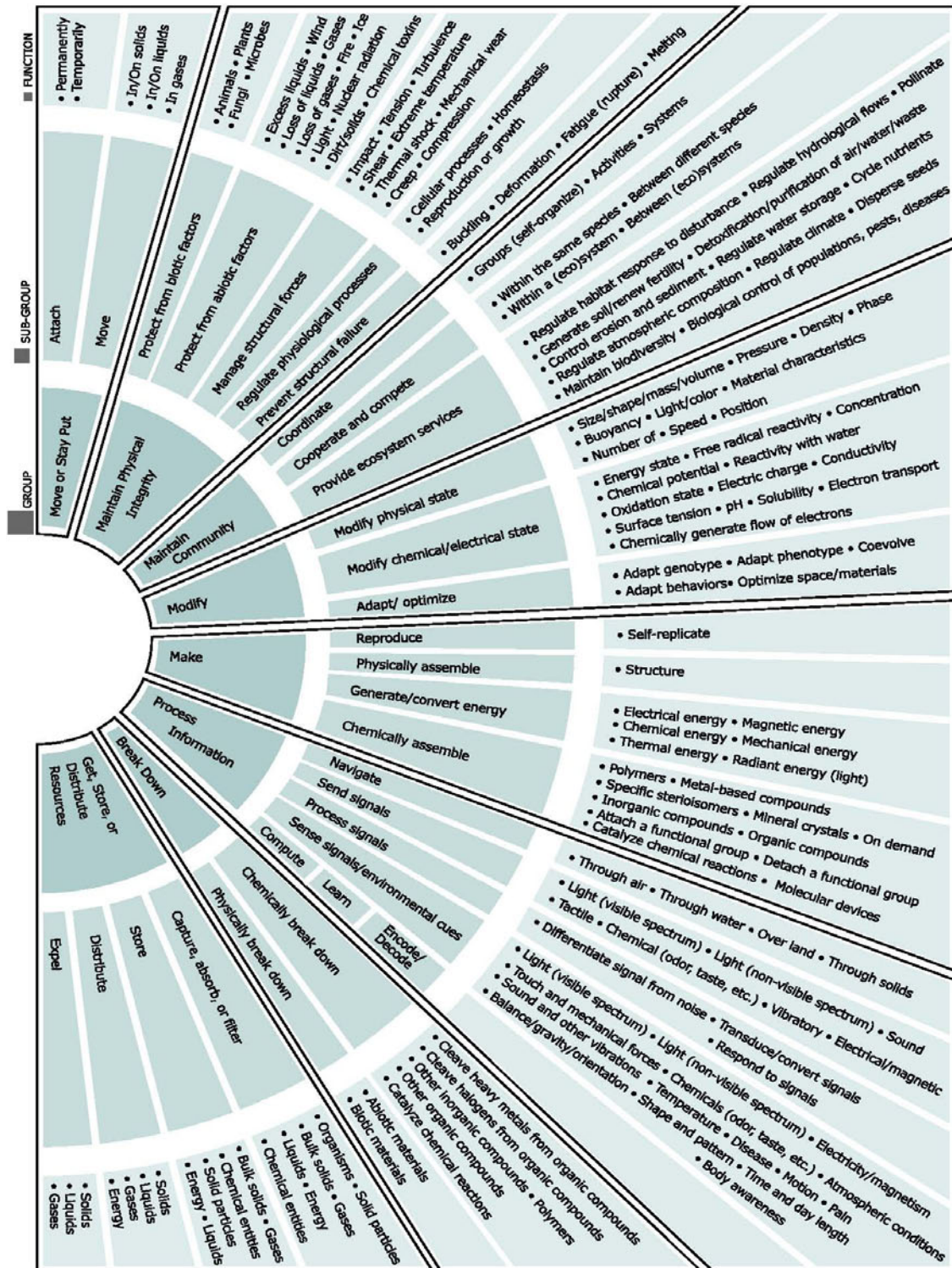
- G. **Identify** - *Develop and refine design briefs based on lessons learned from evaluation*
- Nature works with small feedback loops, constantly learning, adapting and evolving. We can also benefit from this thinking, evolving our designs in repeated steps of observation and development, unearthing new lessons and applying these constantly throughout our own design exploration

Furthermore, the BIOMIMETIC TAXONOMY (Fig.33) expands on the “INTERPRET” step within the Design Spiral, as it relates to functions/issues that need to be resolved, such as the following:

- Store energy/liquids,
- Adapt to wind,
- Generate/convert energy

In addition to the Design Spiral and the Taxonomy, the concept of Life’s Principles (Fig.34) further elucidates the meaning of true sustainability from a “lifecycle” standpoint. This concept can be tied back in to the Design Spiral, wherein the function “EVALUATE” also relates to design “checkpoints” such as:

- Life-friendly materials,
- Fits form to function,
- Feedback loops.



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(c) 2008-2009 The Biomimicry Institute

Figure 33: Biomimetic Taxonomy, the Biomimicry Guild⁷⁰

⁷⁰ Image courtesy: <http://www.biomimicryinstitute.org/about-us/biomimicry-a-tool-for-innovation.html>

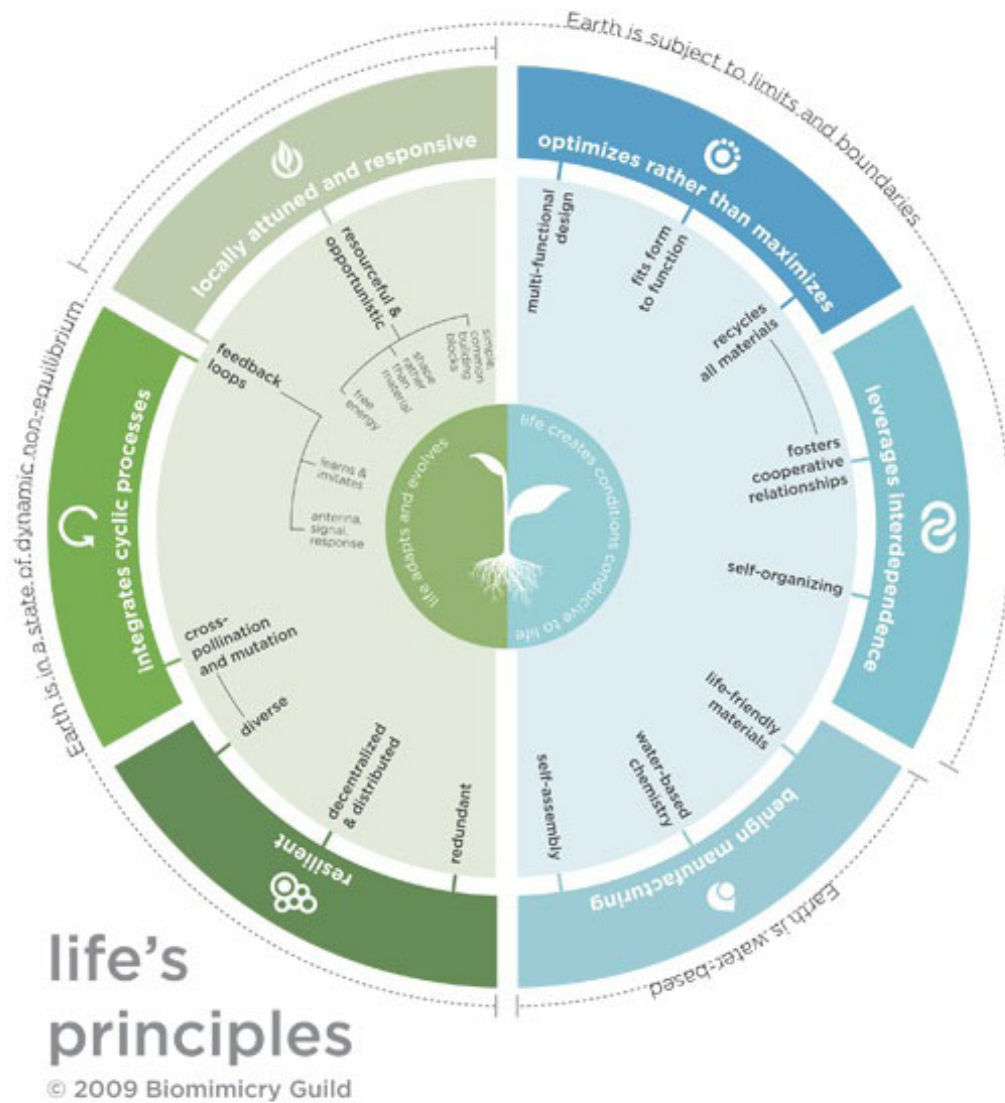


Figure 34: Biomimetic “Life’s Principles”, the Biomimicry Guild⁷¹

71 Image courtesy: <http://www.biomimicryinstitute.org/about-us/biomimicry-a-tool-for-innovation.html>

2.3.2 BIOMIMICRY: Nanotechnology and Design

Nanotechnology originates from the Greek word meaning: dwarf. A nanometer is one billionth (10⁻⁹) of a meter, which is tiny, only the length of ten hydrogen atoms, or about one hundred thousandth of the width of a hair.⁷² Although nanotechnology and the realm of nanoscience are not new, numerous scientists have been doing nanoscience for hundreds of years. Stained-glass windows found in medieval churches contain different-size gold nanoparticles incorporated into the glass — the specific size of the particles creating orange, purple, red, or greenish colors. Albert Einstein computed the size of a sugar molecule to be one single nanometer, while working on his doctoral dissertation.

However, there have been new approaches to developing applied technology, as well as the emergence of the right turn of technology as we have it today. In fact, a committee on nanotechnology was established in the U.S. (the National Nanotechnology Initiative) and the following defining features of nanotechnology were posited:⁷³

1. Nanotechnology involves research and technology development at the 1nm-100nm range
2. Nanotechnology creates and uses structures that have novel properties due to their small size
3. Nanotechnology builds on the ability to control or manipulate at the atomic scale

Seminal studies that characterize and dissect material properties have been performed at the nano-scale. Although this analysis might seem inconsequential to influence large-scale material properties, it might well play an important part in defining the architectural capabilities at the macro level, and thus becoming a key player in the way architects typify and depict different a priori categories of spaces and environments.

According to a new study by the Canadian Program on Genomics and Global Health (CPGGH) at the University of Toronto Joint Centre for Bioethics (JCB), a leading international medical ethics think-tank, nanotechnology applications will help people in developing countries tackle their most urgent problems - extreme poverty and hunger, child mortality, environmental degradation and diseases such as malaria and HIV/AIDS. The study is the first ranking of nanotechnology applications relative to their impact on development.⁷⁴

⁷² Sylvia Leydecker, *Nano Materials: in Architecture, Interior Architecture and Design*, Birkhäuser Architecture, 2008, 12.

⁷³ Ibid, 28.

⁷⁴ Sourced from: medicalnewstoday.com

The top ten (10) nanotechnology applications are:

- Energy storage, production and conversion
- Agricultural productivity enhancement
- Water treatment and remediation
- Disease diagnosis and screening
- Drug delivery systems
- Food processing and storage
- Air pollution and remediation
- Construction
- Health monitoring
- Vector and pest detection and control

It is quite apparently identifiable as to which of these applications can be best integrated into the science and technology within the building sector. There is an accelerated rate at which nanoscience is rapidly establishing in its scope of research; new advancements are being made every single day. Some examples that particularly pertain to architecture include the ability to suppress light reflection by “nanospiked” surfaces,⁷⁵ microcapsules for latent heat storage to use in construction materials⁷⁶, and a “nano vent-skin” designed with micro-turbines within the building skin.⁷⁷

There is a new “self-curing concrete” that exhibits the following properties: can connect development joints, twisting joints and moving structures. Everything begins at the atomic level with the revolutionary blend of eka-atom sifters and narrow crystalline. The material permits the cement to inhale while looking after impermeability. Subsequently, it can cure inside 24 hours while ending up being exceptionally impenetrable to water and different components. Truth be told, the concrete based substance completely joins into cement for a straightforward mixture and takes into consideration self-mending. Assuming that regular splits may as well ever happen in the cement, it will repair them.

75 Lauri Sainiemi, Ville Jokinen, Ali Shah, Maksim Shpak, Susanna Aura, Pia Suvanto, Sami Franssila. “Non-Reflecting Silicon and Polymer Surfaces by Plasma Etching and Replication”. *Advanced Materials*. 23:1 (2010) 122–123.

76 Alton Parrish, “Fraunhofer Institute Creates Microcapsules to Combat Climate Change -120 TWh per Year Needed to Air Condition Europe”. *Nano Patents and Innovations*. (2009), accessed 12-27-2010, URL: <http://nanopatentsandinnovations.blogspot.com/2009/12/fraunhofer-institute-creates.html>.

77 NOS Design Consultancy. “Nano Engineered Details”. *Nano Vent-Skin*. (2008), accessed 1-5-2011, URL: <http://nanoventskin.blogspot.com/>.

Another example of nanotechnology benefiting architectural design, particularly urban oceanfront, is a waterproofing material that has been tested to reveal non-toxic and anti-corrosive properties. It can be applied to any concrete structure (bridges, foundations, water treatment plants, tunnels, hydro electric dams, piles in seawater, airports etc.) Its waterproof layer has a high impervious strength and still has the ability to breathe. Thus the desired effect of ventilation and waterproofing is achieved. In the waterproofing material, "the actuating substance" is exceptionally improved. It is produced out of unsaturated polar particles and is basically an ultra-fine (nm) powder. It will append to the surface of the bond stones by the movement of an additional imperative exceptional helper material, a kind of eka-sub-atomic sifter.

This particular type of material averts concrete deterioration by stopping water infiltration and blocking other corrosives, and has thus far been used in many building, environmental and industrial projects.

Specialists with Berkeley Lab and the University of California, Berkeley, have advanced the first ultra-slim sun based cells contained fully of inorganic nanocrystals and spin-cast from solution. The aforementioned double nanocrystal sun based cells are made from an inexpensive and straightforward to produce solar cells produced out of natural polymers and offer the included preference of being stable in air since they hold no natural materials. MIT specialists attest to having attained one of the turning points in the drive for sustainable clean energy: the advancement of the first practical "artificial leaf". They describe this solar cell as one that imitates the biological function of plant photosynthesis.

"A practical artificial leaf has been one of the Holy Grails of science for decades," said Daniel Nocera, Ph.D., who led the research team. "We believe we have done it. The artificial leaf shows particular promise as an inexpensive source of electricity for homes of the poor in developing countries. Our goal is to make each home its own power station," he said. "One can envision villages in India and Africa not long from now purchasing an affordable basic power system based on this technology."⁷⁸

About the shape of a poker card but thinner, the device is fashioned from silicon, electronics and catalysts, substances that accelerate chemical reactions that otherwise would not occur, or would run slowly. (Fig.27).

⁷⁸ Sourced from NanoArchitecture webpages, accessed: <http://nanoarchitecture.net/>

When the device is set in one gallon of water in daylight, the mechanism could generate enough power to supply a house with power enough for a day's basic activities, Nocera said. It does so by parting water molecules into two components: hydrogen and oxygen. The hydrogen and oxygen gases combine to produce electricity, which could then be stored in a fuel cell for later use. (Fig.35)

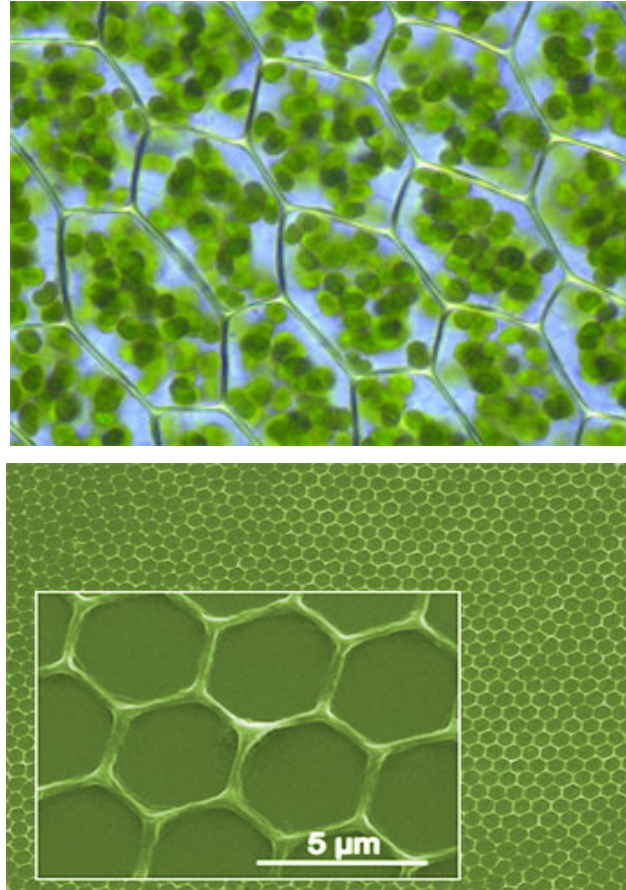


Figure 35: Leaf Structure = Photovoltaics⁷⁹

Nanotechnology also resolves issues that have been left unresolved through past applications in material/physical sciences. One example is the use of molecules to impact studies and further research in thermochemical storage, one of THREE ways to capture solar energy, which are:

- A. Photovoltaics (Solar-to-electricity)
- B. Solar-thermal systems
- C. Thermo-chemical storage

⁷⁹ Image courtesy: www.nanoarchitecture.net

In 2010, the properties of a molecule called “Fulvalene Diruthenium” (FD) (Fig.36) were discovered and put to the thermo-chemical test, whereupon the following properties/characteristics were realized:

- FD undergoes a structural transformation when it absorbs sunlight, putting the molecule into a higher-energy state where it can remain stable indefinitely.
- Triggered by a small addition of heat or a catalyst, it snaps back to its original shape, releasing heat in the process.

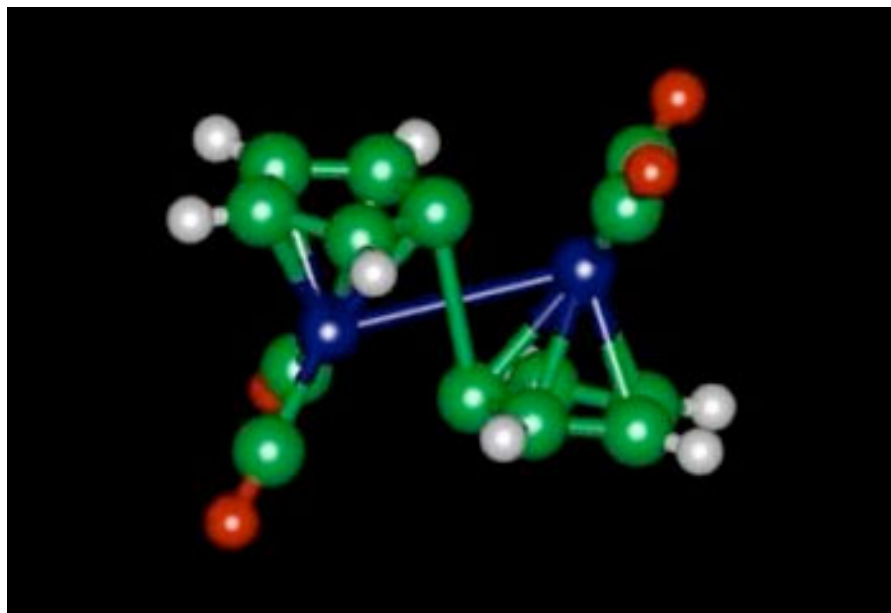


Figure 36: Fulvalene Diruthenium molecule in high-energy state⁸⁰

According to M.C. Roco, chair of the nano subcommittee within the U.S. National Science and Technology Council, he predicts that nanotechnology will form the basis of a "new industrial revolution". He strongly advises for the immediate future saying, "...newly designed advanced materials and manufacturing processes will be built using control at the nanoscale in at least one of the key components, by the year 2015."⁸¹

⁸⁰ Image courtesy: www.nanoarchitecture.net

⁸¹ From online news article accessed on Nanotechnology Magazine, 2012.

2.3.3 BIOMIMETICS AND NANOTECH: Applications in Design

Following is a listing of Biomimetic and Nanotechnological strategies, applicable on the building façade, for the study site in Honolulu.

SUMMARY LIST OF BIO-NANO STRATEGIES: Regulation of LIGHT, AIR, and HEAT through building façades

Response to Light Changes

- A) Heliotropism: Passive/mechanical rotational changes to sun angles: Rotational changes regulated by sun angles
- B) Photoperiodism: Passive/mechanical adjustments in response to light levels: Light-activated actuators and movement: Diurnal and seasonal adaptations

Response to Air Changes

- A) Plant Transpiration & Stoma(ta): Passive/mechanical systems responsive to air/wind direction (Evaporative cooling through nanopores: Stomatex (fabric with tiny pores))
- B) Thigmonastic movement, Cilia: sensory “organelles”: Passive/mechanical systems to tactile cues in environment: Stimulus-activated materials and façade systems

Response to Heat Changes

- A) Shape variation for thermoregulation: Passive/mechanical façade changes and opening actuators: Stimulus-activated shape changes within façade systems
- B) Color change for thermoregulation: Passive/mechanical responses to thermal changes: Color-changing in materials, Increase/decrease material opacity

BIO-to-NANO: Response to Light Changes

A) HELIOTROPISM

Numerous plant species, particularly those in the Leguminosae and Malvaceae families, can situate their leaves in connection to the solar movement and direct rays. The aforementioned developments could be characterized as following the sun's movements (diaheliotropism), or evading the sun (paraheliotropism). Following the sun boosts the measure of immediate sun based radiation a leaf appropriates, while paraheliotropism decreases the amount a leaf receives. The aforementioned leaf developments are not development developments; rather they are fast, reversible developments according to turgor changes in organ cells at the base of the leaf petiole called a pulvinus.⁸²

Numerous desert annuals, plants that develop according to capricious rains show heliotropic developments. The aforementioned following developments can build radiation interference, photosynthesis and development rates -worthwhile lands in a nature's domain. Some of the aforementioned annuals additionally demonstrate paraheliotropism: this shifting caused as a result of water stress, subsequently augmenting life by diminishing leaf temperatures and water misfortune as soils dry out.

Biomimicry of heliotropic plants – more efficient solar panels

Current solar-tracking-photovoltaic panels include the utilization of engines and electronic control frameworks, yet a biomimetic heliotropic photovoltaic panel can now be made with the utilization of several alternative materials and designs, ones that are much more affordable. Therefore, this can be easily seen as technology that can be adapted to less affluent communities and economies. Solar-tracking capabilities in these photovoltaics can cause higher efficiencies by about 35-40 percent than static mounted. Student team “Heliotrope” from MIT were instrumental in designing exactly such an efficient, and yet inexpensive technique.⁸³ Their design utilizes the concept of solar tracking by plants, and they translated this into ways by which the base material changes its inherent properties in response to the fluctuations in temperature between sunny and shaded areas of a microclimate. Unlike currently operated systems that work in a similar fashion, yet uses mechanical energy and systems to aid in the movement, team Heliotrope's biomimetic design needs no external power source, and instead uses clean solar energy to operate in a

⁸² “Heliotropic leaf movements in plants”, accessed 1-10-12, at URL: <http://www.biol.umd.edu/Forsethlab/leafmovements.htm>

⁸³ David Chandler, “Sun-tracking device wins student prize”, *MIT News Office*, accessed on 2-1-12, available at URL: <http://web.mit.edu/newsoffice/2008/madmec-0919.html>

completely passive method. After much experimentation with various materials and polymers, the ideal system according to the students is one that mounts solar panels on a metallic arch structure made of aluminum and steel paired together. When a light and heat source is applied to one side of the system, they established the bending of the arch, which then as a consequence, tilts the material panel toward the light source (Fig. 37).⁸⁴



*Figure 37: Team Heliotrope's sun tracking technology*⁸⁵

Artificial Heliotropism in Nanocomposite solar panels

Also inspired by heliotropism seen in nature, scientists have assembled nanocomposites to realize another passive method to achieving sun-tracking solar panels. It is made of reversible photo-thermo-mechanical liquid crystalline elastomer (LCE) nanocomposite with “..direct actuation capability.. no need for motor-driven sensors or actuators.”⁸⁶ Active systems and the use of mechanical power and electrical energy consumption is thereby also unnecessary, and this novel have, upon laboratory and field-testing, shown full-range (tracking all sun angles) heliotropism.

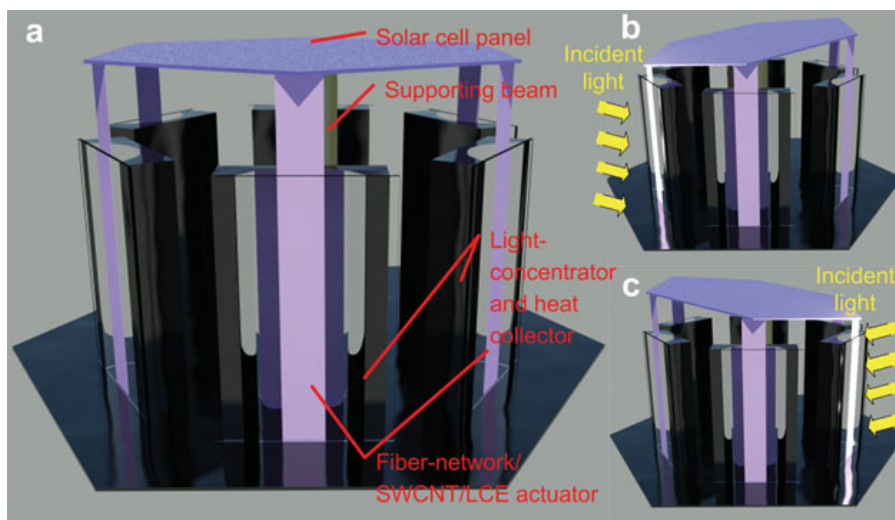
These LCEs have the ability to alter their orientation order when exposed or retracted from light sources. Such a change in turn induces a mechanical and physical change in the macro properties

⁸⁴ Ibid.

⁸⁵ David Chandler, “Sun-tracking device wins student prize”, *MIT News Office*, accessed on 2-1-12, available at URL: <http://web.mit.edu/newsoffice/2008/madmec-0919.html>

⁸⁶ “Direct Sun-Driven Artificial Heliotropism for Solar Energy Harvesting Based on a Photo-Thermomechanical Liquid-Crystal Elastomer Nanocomposite”, C Li et al, *Adv. Funct. Mater.*, accessed September 2012, DOI: 10.1002/adfm.201202038

of the elastomer, which then contorts or bends when light activates it (Fig.38), and upon subsequent removal of the same light source, the mechanical changes are released to enable the material to reach its original, relaxed state. One limitation of this study was that the LCEs are typically only responsive to light of specific wavelengths. This prompted the researcher to increase the sensitivity of the LCEs by embedding carbon nanotubes (CNTs) in the base material. This magnifies the elastomeric competency of the materials, in response to white light.



*Figure 38: Actuators contract to make the solar cell face the sun.*⁸⁷

Thus, the research material was made able to respond to sunlight with the utilization of only a concave mirror behind to concentrate and focus the light on the actuator.

⁸⁷ "Solar cell meets sunflower", Chemistry World, accessed September 2012, available online at URL: <http://www.rsc.org/chemistryworld/2012/08/solar-cell-meets-sunflower>

B) PHOTOPERIODISM

Plants were discovered to display both diurnal and seasonal changes, in order to maintain internal equilibrium and also to respond to environmental cues that help with necessary functions such as flower and fruit production, seed germination, and retaining dormancy during certain times within the year. The phenomenon exhibited by plants to respond and adapt to varying lengths of day and night is known as photoperiodism.

Night length affects blooming in many plants (Fig.39) “..short-day (long-night) plants such as the chrysanthemum bloom ..night lasts *longer*.. if that critical night length is interrupted with a flash of light, the plant fails to bloom.”⁸⁸

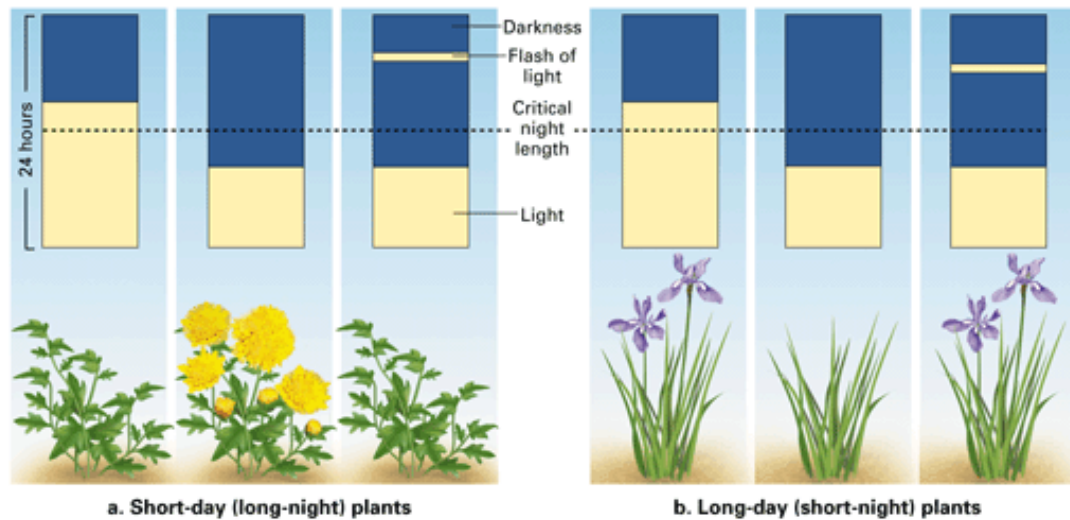


Figure 39: *Diurnal and seasonal adaptations in plants*⁸⁹

How does a plant monitor day length as the seasons change? The existence of pigmented proteins or ‘phytochromes’ helps with this day-night-time detection by plants. Once the phytochromes sense the abundance of sunlight at daybreak, this light absorption activates a shape change in their structure. Similarly, after sunset, the phytochromes gradually change back to their inactive form. Such responses to environmental sunrise/sunset cues, in are therefore necessary to activate the plant’s biological clock in order to indicate the proportions of day and night within a 24-hour period.

⁸⁸ Plant Responses to Light: Phototaxis, Photomorphogenesis, and Photoperiodism, accessed online at: <http://www.biologie.uni-hamburg.de/b-online/e30/30.htm>

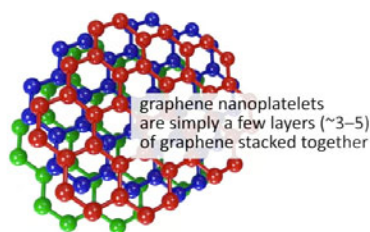
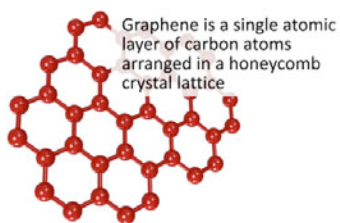
⁸⁹ Plant Responses to Light: Phototaxis, Photomorphogenesis, and Photoperiodism, accessed online at: <http://www.biologie.uni-hamburg.de/b-online/e30/30.htm>

Graphene Nanoplatelet-Based Photomechanical Actuators

Graphene's incredible discovery in 2004 led to intense analysis and scrutiny of its superior mechanical, structural, and thermal properties. Various scientists have been working on photomechanical actuators that are infused or integrated with graphene nanoplatelets that would then respond to achieve strains or tactile pressures upon illumination. By combining graphene with soft elastomeric materials such as PDMS, the group has created graphene/polymer composites whose responses to near-infrared (NIR) illumination depend on applied pre-strain.

Reversible contraction and expansion were observed, corresponding to reduced levels of pre-strains (3–9%); furthermore, there was also concurrent display of reversible expansion. In a similar fashion, these actuators were found to respond in reversible contraction at pre-strain levels that were high (15–40%). In contrast to conventional photomechanical actuating materials such as polyvinylidene fluoride (PVDF), these graphene-based actuators were about a thousand times more powerful in the conversion of optical to mechanical energy (with a factor of ~ 7 MPa/W).⁹⁰

The researchers also then devised a “black box” system that was imbued with remote operative capability designed and built to automate processes of pre-strain control and infrared illumination intensity (Figs. 40-42) The equipment was interfaced with computers that controlled test sequencing, data logging and analysis. The data analysis revealed that it was possible to perform multiple actuation and relaxation, and also that there was no significant degradation, even after significantly lengthy cycling periods.⁹¹



90 James Loomis, Ben King, Tom Burkhead, Peng Xu, Nathan Bessler, Eugene Terentjev and Balaji Panchapakesan, “Graphene-nanoplatelet-based photomechanical actuators”, *Nanotechnology* 23 (4), February 2012.

91 James Loomis, Ben King, Tom Burkhead, Peng Xu, Nathan Bessler, Eugene Terentjev and Balaji Panchapakesan, “Graphene-nanoplatelet-based photomechanical actuators”, *Nanotechnology* 23 (4), February 2012.

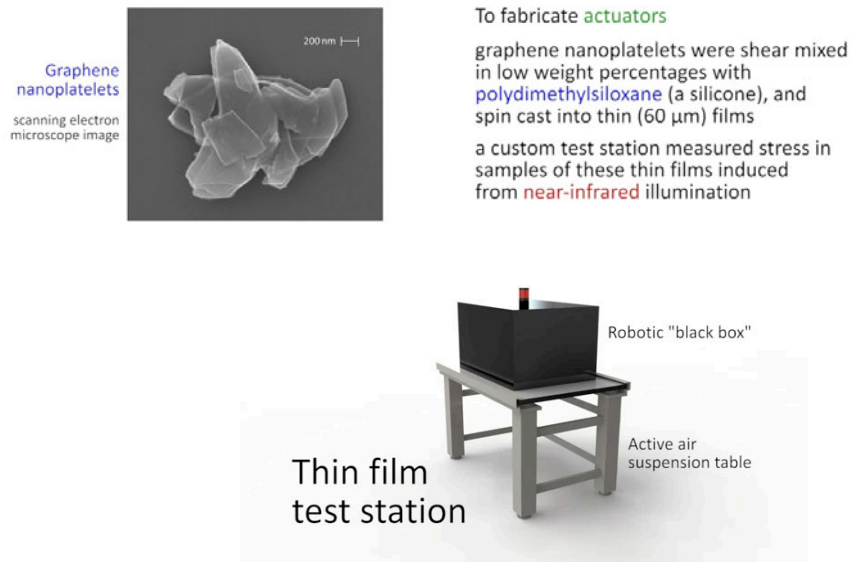
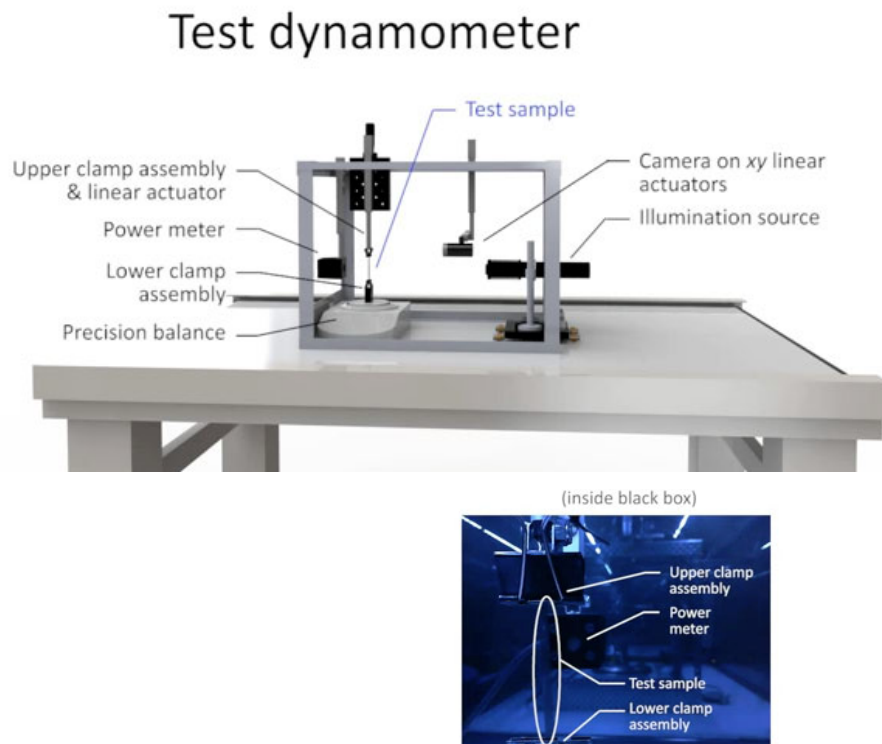


Figure 40: Series 1: Explaining in sequence, thin film test station



Near-infrared illumination induces elastic responses in graphene nanoplatelet-polymer composites
These responses are pre-strain dependent

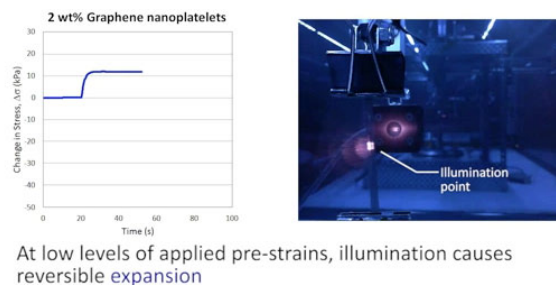


Figure 41: Series 2: Explaining in sequence, the illumination stimuli

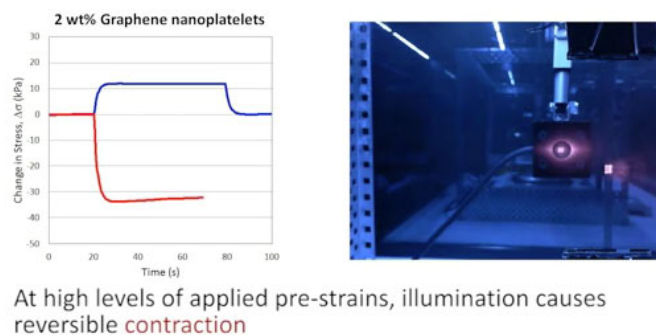


Figure 42: Series 3: Reversible expansion, contraction, upon removal of photo stimulus⁹²

⁹² James Loomis, Ben King, Tom Burkhead, Peng Xu, Nathan Bessler, Eugene Terentjev and Balaji Panchapakesan, "Graphene-nanoplatelet-based photomechanical actuators", *Nanotechnology* 23 (4), February 2012.

BIO-to-NANO: Response to Air Changes

A) STOMATAL TRANSPIRATION

Stomata are small openings in the cuticle of leaves that allow plants to regulate the movement of air between the interior and exterior environment.

Stomatal function occurs as a result of having “guard cells” on the underside of the leaf push against each other to generate an opening (Fig.43). The thickened nature of the pore’s edge bends, without sufficient mechanical capability to bend. Simultaneously, an aperture is created at the pore opening. Thus, the overall structure and form of the stomatal cells are retained, even as the inflating chambers at each end force these sections to stay open.⁹³

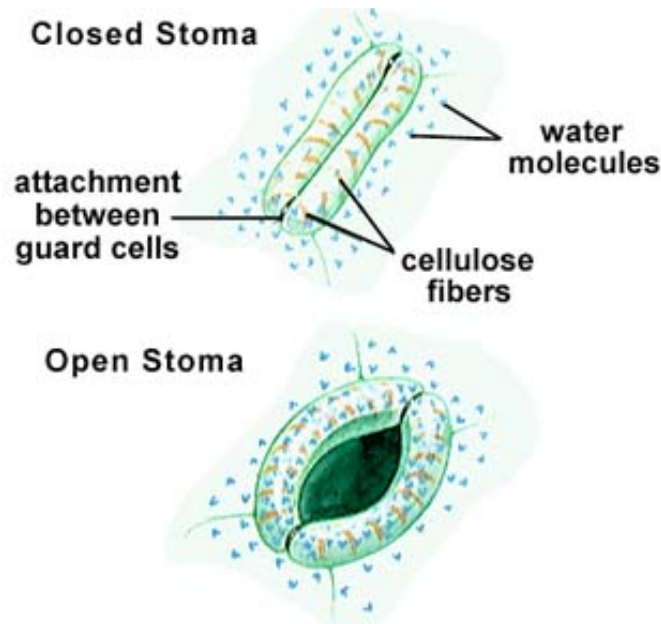


Figure 43: Stomatal structure and function⁹⁴

“Breathable” Building Envelopes

Instead of windows, building envelopes might be better served equipped with “stomata-like” openings on the facades, for instance, the “Stomatex” fabric.⁹⁵ If different sets of “building skin stomata” can operate under differently controlled responses to temperature, light, wind and

⁹³ “Plants in Action: Adaptation in Nature, Performance in Cultivation”, accessed 1-11-11, URL: <http://plantsinaction.science.uq.edu.au/edition1/?q=node/447#770>

⁹⁴ “Plants in Action: Adaptation in Nature, Performance in Cultivation”, accessed 1-11-11, URL: <http://plantsinaction.science.uq.edu.au/edition1/?q=node/447#770>

⁹⁵ “Stomatex Fabric: Applications and Concept”, accessed 1-16-11, URL: <http://www.stomatex.com/concept.htm>

humidity levels separately, then it would be possible to integrate them into building design and façade treatments. (Similar to “guard cells” and “stomatal movement” in plant cells).

Skin-like sensors

Scientists and researchers from Stanford have developed a sensor that takes advantage of the flexibility of carbon nanotubes (CNTs), by likening their properties to spring-like motion. Single-walled CNTs that together make up a transparent film act like these springs, with each one having the ability to accurately sense the difference between a push-force and a pull-force. Also, the pressure sensory range is enormous (from a firm pinch to thousands of pounds). This sensor is perfectly expandable, and once released, contracts back into its original shape.⁹⁶

Darren Lipomi, a postdoctoral researcher in Bao's lab and an integral part of the research team, notes that the sensor's adaptation to varying degrees and magnitudes of pressure is strong enough to not result in any permanent change to the shape. The preparation of the sensor involves a process of “...spraying nanotubes in a liquid suspension onto a thin layer of silicone, which is then stretched”.⁹⁷ (Fig.44) When the nanotubes are spray-painted onto the silicone, they were found to settle in arbitrarily oriented mini clumps, aka “nano-bundles”.

However, it was discovered that once the silicone is stretched and then released, a few nano-bundles get pulled into alignment; afterward upon rebounding, the nanotubes buckle and form little nanostructures that look like springs. "After we have done this kind of pre-stretching to the nanotubes, they behave like springs and can be stretched again and again, without any permanent change in shape," Bao said.

It is critical to retain similar conductivity in both the stretched and unstretched forms, this is due to the fact that these nano-sensors working as electrodes are then able to sense and accurately quantify the force being applied to them through these spring-like nanostructures.

⁹⁶ “Stanford researchers build transparent, super-stretchy skin-like sensor”, *Stanford Report*, October 24, 2011, accessed 1-14-12, URL: <http://news.stanford.edu/news/2011/october/stretchy-skinlike-sensor-102411.html>

⁹⁷ Ibid.

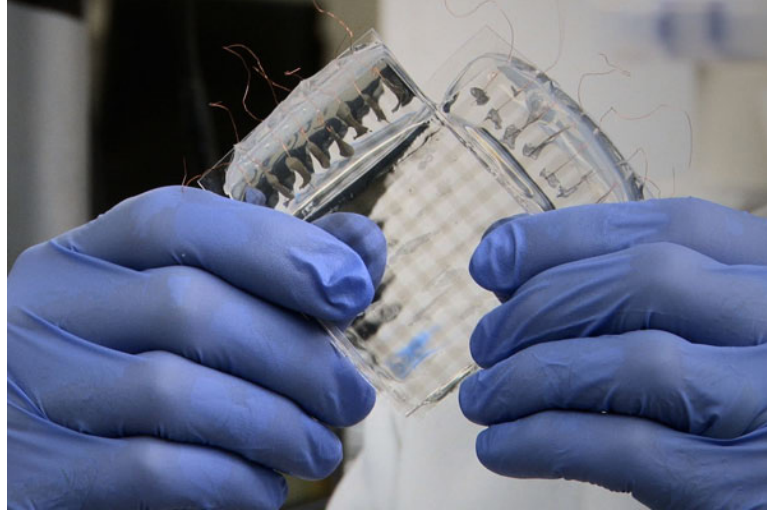


Figure 44: Image of nanotube-coated silicone (dimethicone) material⁹⁸

Biomimetic Micropump

Li et al. present a micropump in their research, where the design and operation of a biomimetic micropump (based on water potential difference in plants) are discussed. “.48- μm thick metal screen plate and 102- μm diameter micropores .. gel sheet with nanopores of 100 nm diameter.⁹⁹ The micropores in the screen plate imitate the stomata to regulate the flow rate of the micropump. Similar to the mesophyll cells around a stomata in a plant, the agarose gel sheet with its nanopores acts as a guard layer, using water loss from the nanopores and resulting water potential to have fluid motions of solution.

B) THIGMONASTIC MOVEMENT

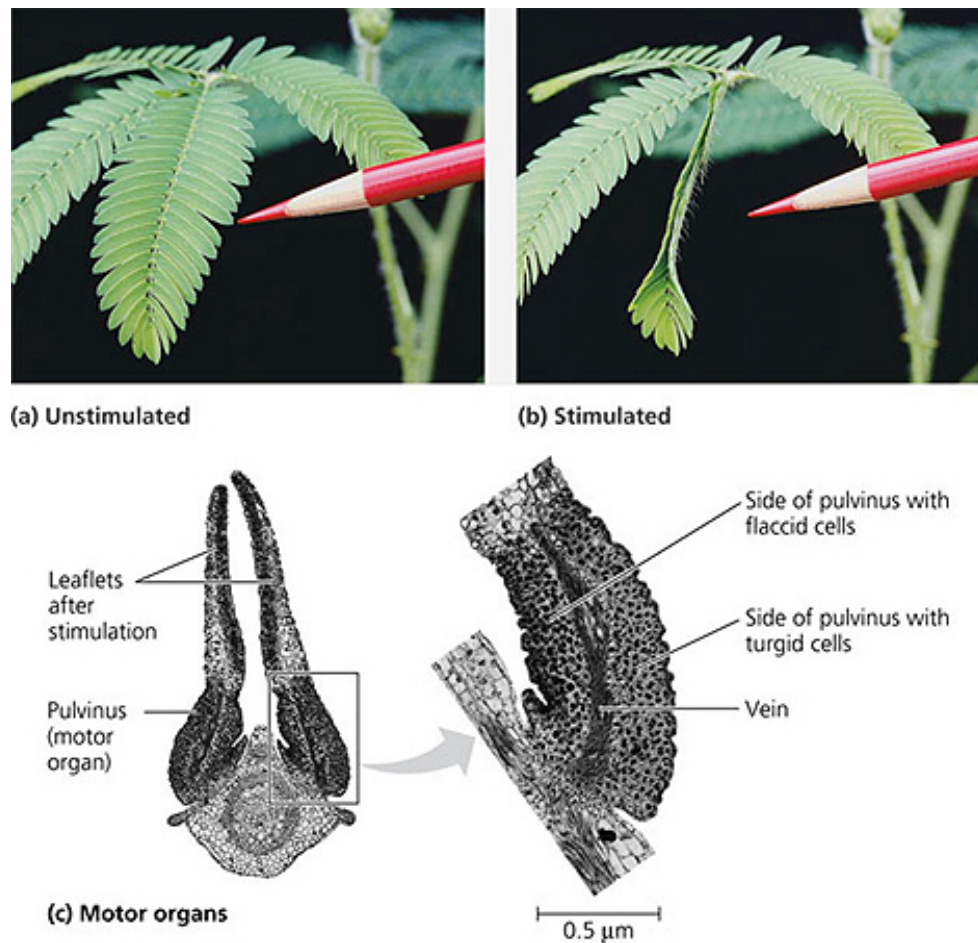
The *Machaerium arboreum*, a vine growing in the Panamanian rainforests, survives the heavy rainfall by employing thigmonastic movements. Through a series of changes in the environment that results in sugar loading into the “apoplast” (space outside plasma of cells), which in turn leads to changes in the potassium ion levels. This ultimately leads to water loss within specialized cells located at the base of each leaflet. A pulvinus is a sort of plant motor structure, an enlarged area at the base of a movable plant structure (petiole, leaflet attachment to rachis, node, etc.) that can produce movement by a change in turgor pressure in some of its cells.

⁹⁸ “Stanford researchers build transparent, super-stretchy skin-like sensor”, *Stanford Report*, October 24, 2011, accessed 1-14-12, URL: <http://news.stanford.edu/news/2011/october/stretchy-skinlike-sensor-102411.html>

⁹⁹ Jing Li; Chong Liu; Kai Zhang; Xue Ke; Zheng Xu; Chun Li; Li Wang, “A micropump based on water potential difference in plants,” *Microfluidics and Nanofluidics* (December 2011), 11 (6), 717-724.

It may be possible to employ moisture-control valves located on external building facades to regulate moisture inside spaces. If possible, “ultra-sensitive” tracking sensors on the façade of the building could control these valves, so that the system updates continually as it responds to external changes and influences within the environment. The energy required to operate these valves could be from tactile stimuli (water facades or raindrops, etc.)

A “kinetic” building envelope that internally responds (by change in angle or opening/closing mechanisms) to tactile stimuli could also be seen as cues in the environment.



*Figure 45: Thigmonastic movement in leaves*¹⁰⁰

Microbelt Device Generates Electricity

University researchers at Wisconsin-Madison have established a small mechanism, which is able to convert the human breath and resulting airflow into electricity. The main challenge that they

100 Plants and the Environment: Tropisms, Circadian Rhythms and More, accessed online at URL: http://www.bio.miami.edu/dana/226/226F08_21.html

initially faced was to create something small and flexible enough to sense normal respiratory air speeds, which are typically close to two meters per second. The device incorporates a plastic microbelt made of polyvinylidene fluoride (PVDF) material, which vibrates when passed by low-speed airflow. The microbelt's responses to the small pressure changes (caused by human respiration) stimulates a piezoelectric effect, resulting in a production of electrical charge.¹⁰¹

In the picture below (Fig.46), the small yellow part represents the microbelt while the other parts form a simulated lung to generate the necessary airflow. Researcher discovered and measured that the PVDF microbelts were able to generate sufficient electrical energy from low speed airflow for the sustained operation of small electronic devices.

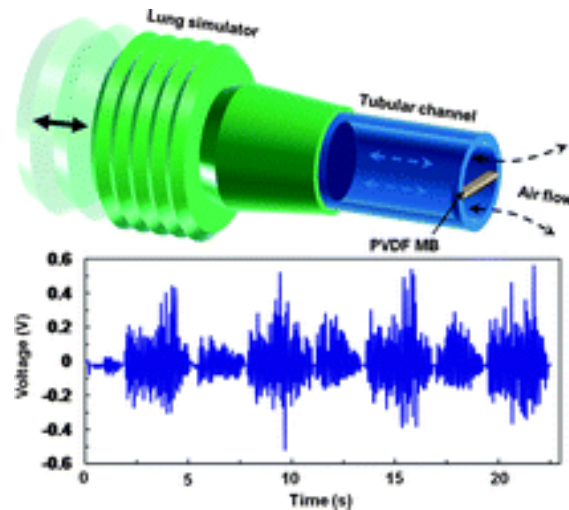


Figure 46: PVDF microbelt in lung simulator

Cricket inspires ultra sensitive airflow sensor

The little hairs on the midriff of a cricket have roused analysts at the Mesa+ Institute for Nanotechnology University of Twente to make another sort of sensor which is ultra-sensitive to air movement. The hairs on a cricket's abdomen - on the projections known as 'cerci' - formed the source of inspiration. The aforementioned sensors can additionally be tuned quite absolutely for a certain reach of frequencies, and within that specific range of frequencies, the hairs are 10 times more responsive.

Without warning, the discovery made was that the synthetic cricket hairs showed up as being

¹⁰¹ Chengliang Sun, Jian Shi, Dylan J. Bayerl and Xudong Wang, "PVDF microbelts for harvesting energy from respiration", *Energy & Environmental Science* (Issue 11, 2011),

more delicate to a particular recurrence and air frequency. It should be noted that the hair itself was not altered; nevertheless, the improved responsiveness to airflow is attained by altering it's the firmness factor of the spring electronically.¹⁰²

The synthetic cricket hair is an example of biomimicry. These hairs assist in a capability of feeling and listening to possible enemy approaches, and the inherent sensitivity of these hairs also help in guesstimating their distance and direction from their predators, by utilizing this infallible method (Fig. 47).

The simulated version of the cricket hairs involves preparing polymer SU8 hair (about 0.9mm long). Similar to the workings of the cricket hair, the base plate upon which the synthetic hairs are suspended is then able to register the mildest changes and adjustments in movements at places where the hairs are attached. When connected to electricity, the measure of the physical movement of the hairs results in a corresponding electrical capacity change in the flexible microsystem plate.

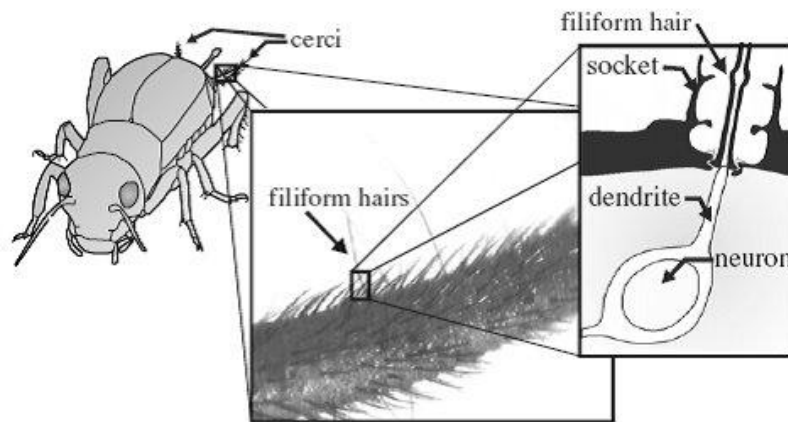


Figure 47: Diagram of cricket hair or “cerci”

102 H. Droogendijk, C.M. Bruinink, R.G.P. Sanders and G.J.M. Krijnen, “Non-resonant parametric amplification in biomimetic hair flow sensors: selective gain and tunable filtering”, *Applied Physics Letters* (accepted, pending online publication), accessed at URL: http://www.nanomagazine.co.uk/index.php?option=com_content&view=article&id=1591:cricket-inspires-ultra-sensitive-air-flow-sensor&catid=38:nano-news&Itemid=159

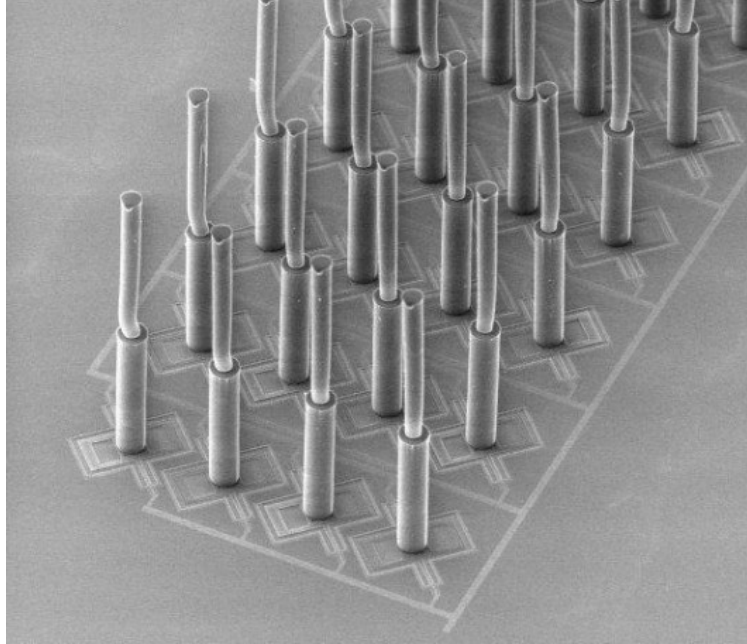


Figure 48: Synthetic (SU8 polymer) sensors

Sensitivity to a range of barely noticeable movements are registered by thickening the base of the synthetic hair, while keeping the top narrow and of a thinner cross-section. Potential applications include direction sensors used by robots and the study of very specific airflows.¹⁰³

¹⁰³ H. Droogendijk, C.M. Bruinink, R.G.P. Sanders and G.J.M. Krijnen, “Non-resonant parametric amplification in biomimetic hair flow sensors: selective gain and tunable filtering”, *Applied Physics Letters* (accepted, pending online publication), accessed at URL: http://www.nanomagazine.co.uk/index.php?option=com_content&view=article&id=1591:cricket-inspires-ultra-sensitive-air-flow-sensor&catid=38:nano-news&Itemid=159

BIO-to-NANO: Response to Heat Changes

A) SHAPE VARIATION FOR THERMOREGULATION

In many large trees, leaves from the top of the tree or with a southerly exposure differ markedly in shape from those leaves lower in the canopy or with a northerly exposure. This adaptation dissipates heat from leaves that receive more solar radiation. For example, a broad leaf in bright sunlight and still air may be 10-20 degrees C warmer than its surroundings. The upper thermal limit of leaves is 55-60 degrees C, thus leaves exposed to constant sunlight are more susceptible to overheating than those leaves in the shade.¹⁰⁴

Sun leaves on some trees have adapted to dissipate more heat by being smaller, thicker, and more deeply lobed. This makes the surface of a sun leaf a shorter distance from a free edge; and, since the boundary layer thickness increases with distance from an edge, it will have a thinner boundary layer of heated air.

Studies show that by varying these characteristics of leaf shape, sun leaves are significantly better heat exchangers than shade leaves. Additionally, leaves with larger teeth, or lobes (e.g., maple leaves), are able to dissipate more heat by convective means than those without.¹⁰⁵

Dielectric elastomers

(DEs) are smart material systems which alter in shape and structure, upon application of large strains (up to 300%) DEs are also part of the group of electroactive polymers (EAP). It has been discovered that DEA (dielectric elastomers) have the ability to convert mechanical and physical energy sources to forms of electrical energy (Fig.49).

¹⁰⁴ Kerry L Bright, Mark D Rausher, "Natural selection on a leaf-shape polymorphism in the ivyleaf morning glory (*Ipomoea hederacea*)", *Evolution: International Journal of Organic Evolution*, 62 (8), 2008, 1978-1990

¹⁰⁵ Ibid.

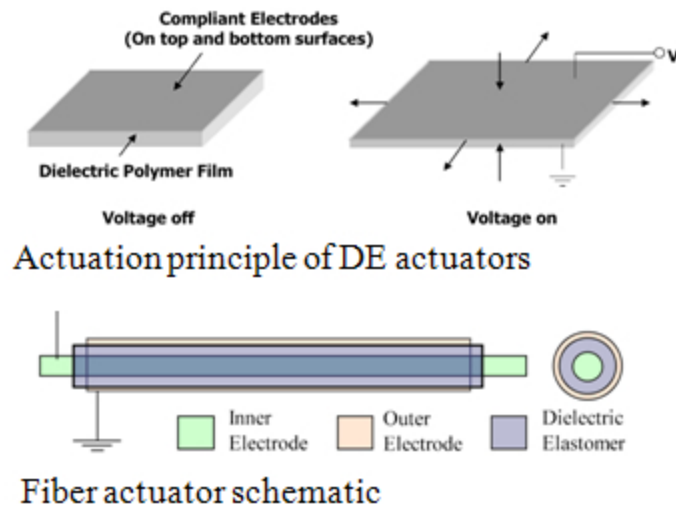


Figure 49: Working mechanism of dielectric elastomers¹⁰⁶

¹⁰⁶ Image courtesy of: "Dielectric Elastomer based Prototype Fiber Actuators", accessed at <http://www.tx.ncsu.edu/research/researchgroups/smarttextiles/projects.cfm>, 2011

B) COLOR CHANGE FOR THERMOREGULATION

The African reed frog, as with many other amphibians, also uses iridophore cells for reflectance. This is because the arrangement of iridophore cells in layers that run parallel to the skin surface maximizes reflectivity of solar radiation. Some lizards use iridophore cells, wherein rapid, thermally induced color change arises from alterations in the packing between layers of reflective crystalline platelets inside the cells. The African reed frog and the green tree frog are also two species that use a variation of this strategy to thermoregulate.¹⁰⁷

The eyelid and pupil regulate the amount of light that may pass into the eye and through the eye cells. Color and shape change occurs in amphibian skin and in squids, to achieve protection from predators as well as for thermoregulation.¹⁰⁸

Iridophore cells & glazing technology

Dichromatic/polychromatic structure of the “skin” could well act as a thermoregulatory device, propelling connected parts to be stimulated. The ability of a building skin to change color would be highly conducive to affecting the right amount of reflectivity, light transmittance and radiant heating within the interiors of the building.

Porous Nanocoating For Smart Windows

Vanadium dioxide (VO₂) has, as a relatively new material, has generated substantial technological relevance for the fields of optics and electronics, and as a favorable contender for producing smart windows; it has been discovered and researched to find that VO₂ can transition from displaying a clear, transparent, semiconductive characteristics at low temperatures while allowing infrared radiation through, to an impervious, metallic state of material phase at high temperatures,, the latter characteristics operational while still permitting visible light to get through. Furthermore, the speed with which VO₂ transition through this phase change is renowned among the world’s best materials (Fig. 50) that effectively changes the material from a metal to an insulator. The phase change takes place at about 68 degrees Celsius.¹⁰⁹

107 Harun Yahya. 2002. *Design in Nature*. London: Ta-Ha Publishers Ltd. 180 p.

108 Crookes, W. J.; Ding, L. L.; Huang, Q. L.; Kimbell, J. R.; Horwitz, J.; McFall-Ngai, M. J. 2004. Reflectins: The Unusual Proteins of Squid Reflective Tissues. *American Association for the Advancement of Science*. 235-238 p.

109 Litao Kang et al., “Nanoporous Thermochromic VO₂ Films with Low Optical Constants, Enhanced Luminous Transmittance and Thermochromic Properties”, *ACS Appl. Mater. Interfaces*, 2011, 3 (2), 135–138

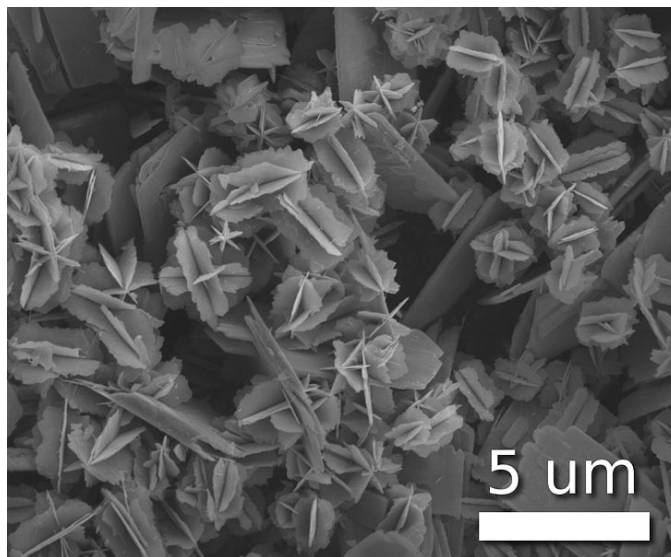


Figure 50: Nanostars properties affect macro properties of VO_2 ¹¹⁰

Till date, VO_2 hasn't been recognized to be especially suited for expansive applications related to smart-windows; this is because of its low luminosity in transmittance, as well as its solar-oriented regulating capacity. Systems to enhance the aforementioned lands, for example through doping or composites, have brought about trade-offs to settle and reach a cohabitated consensus of material properties involving its luminous transmittance and thermochromic properties.

It is now very much within the realm of possibility to prepare thin film VO_2 thin-films with a manageable morphology (including grain size and porosity), thanks to the expert work of analysts at the Shanghai Institute of Ceramics, Chinese Academy of Sciences (SICCAS).¹¹¹ Alteration of these nano-level properties (raising porosity and lowering optical constants) has been found to result in enhanced performance levels such a much higher transmittance of visible light and improved solar modulating ability. The researchers argue that a single-layer film of this thickness clearly display luminous transmittance and solar modulating ability values equivalent to those of five-layered $\text{TiO}_2/\text{VO}_2/\text{TiO}_2/\text{VO}_2/\text{TiO}_2$ films with optically optimized structures.¹¹²

¹¹⁰ Image Courtesy of <http://en.wikipedia.org/wiki/File:Nanostars-it1302.jpg>

¹¹¹ Litao Kang et al., "Nanoporous Thermochromic VO_2 Films with Low Optical Constants, Enhanced Luminous Transmittance and Thermochromic Properties", *ACS Appl. Mater. Interfaces*, 2011, 3 (2), 135–138

¹¹² Ibid

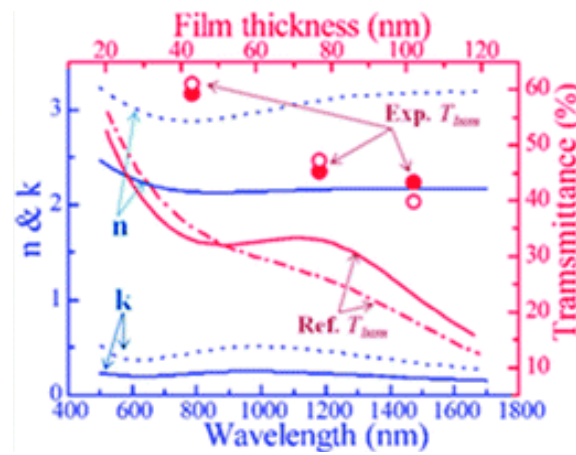
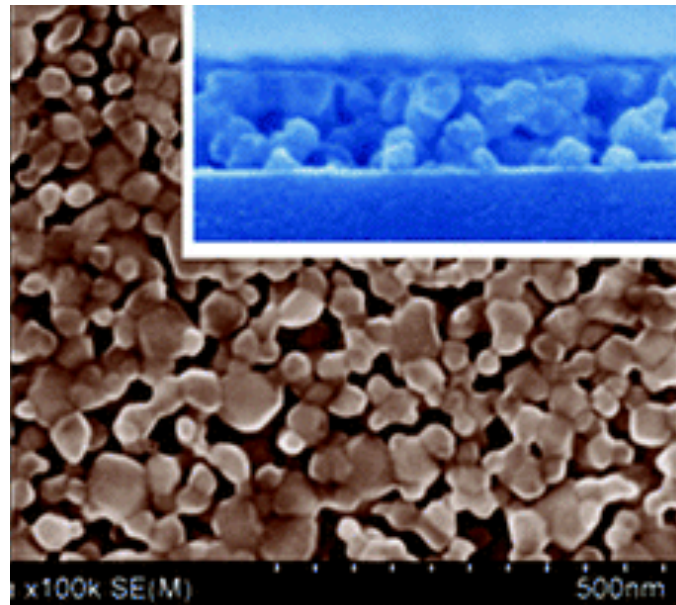


Figure 51: VO_2 Film porosity and thickness¹¹³

¹¹³ Image Courtesy of: "Porous Nanocoating for Windows", accessed at www.nanoarchitecture.net

2.4 BIOPHILIA: A Study

2.4.1 INTRODUCTION TO PSYCHOPHYSIOLOGY

DEFINITION OF PSYCH-O-PHYSI-O-LOGY: Study of mind-body interactions.

Physical responses and bodily changes originate as a result of the human psyche. It is the use of an emotional and physiological tool to test people's response/reaction to these new ideas and technologies.

There is an increasing interest in the study of psychophysiology as a means of understanding and further exploring the realm of responsive architecture. This idea stems from the fact that over the past few decades, environmental aesthetics has emerged as a relatively new area of expertise in landscape urbanism and architectural planning.¹¹⁴ It is important for architects to know not only about the building's physical components, but also crucial to understand the psyche of the people they are designing for. Biophilia is the theoretical idea that is concerned with bringing humans back into contact with nature.

Biophilia and biophilic elements stimulate the senses and helps the mind to think outside of the box. Over the past few decades, scientists have been researching the neurological effects of humans and nature within a built environment to establish how architecture and nature can influence creativity and productivity. Functional and aesthetic considerations being a normality of a designer's "bag of tricks", further depth and meaning can be added when a person's psychological responses to design elements are explored in a thorough fashion.

Response recording for architectural projects, such as in this dissertation, will provide a measurable way of quantifying and validating the design output, and linking to "the whole":

Parts ---→ Process ---→ People.

¹¹⁴ Roger S. Ulrich, "Natural versus Urban Scenes: Some Psychophysiological Effects". *Environment and Behavior* 13:5 (1981) 523-56.

2.4.2 EVOLUTIONARY AND ENVIRONMENTAL PSYCHOLOGY

In order to fully understand the “why” behind the human physiological responses, there is a need to understand the characteristics of the space itself. What exactly do people respond to? If research has been done with specific environmental categories, could those frameworks/guidelines be possibly replicated to frame other settings? So what would be some general spatial characteristics? Different models have been proposed to explain human aesthetic reactions to environments. In general, such aesthetic reactions are framed as ‘liking’ or ‘disliking’ responses. However, several studies and research also place a framework for non-aesthetic reactions and responses.

Habitat comprehension: Prospect and Refuge

According to early theories, human beings’ preference for landscapes correlates with two environmental qualities: namely prospect and refuge. The notion of ‘prospect’ refers to settings or landscape elements that facilitate obtaining information about the environment. A typical example is a hill, which aids to visually access and inspect the surrounding area, by which predators or potential sources of food could be detected. Similarly, ‘refuge’, as a theme, points to locales that can offer shelter and protection. One important and well-known case is a cave, which can protect against predators and adverse weather conditions. Appleton theorized that the evolutionary adaptations and genetic make-up have provided humans with ingrained, inborn “settings” to qualify these characteristics within a scene, and that prospect and refuge are part of overall survival skills.

Habitat information: Kaplans’ model

Rachel and Stephen Kaplan improved a qualified information based natural model, otherwise called the "preference matrix". In this model, toward one side of the matrix, the individual could be actively "included" in an environment (e.g. investigating the setting). Then again, the individual can attempt to "grasp" nature. Kaplan contends that the transition between the two aforementioned mentalities is expedited by four landscape characteristics.

Rachel and Stephen Kaplan developed an information-based environmental model, also known as the “preference matrix”. In this model, it shows that in the preference matrix/ spectrum, the person can be actively ‘involved’ in an environment (e.g. exploring the setting) on one end of the matrix. Alternatively, the person can try to ‘understand’ the environment. Kaplan argues that these two attitudes are facilitated by four structural landscape properties, which have been extracted from a large number of studies in landscape aesthetics.

The Kaplans described particular settings dependent upon the qualities of the space that they considered, and made divisions dependent upon spatial designs: Open-Undefined or ones that need clear, spatial definition, Spacious-Structured that hold courses of action of spatial components for example trees, water, milestones, edges, and so forth), Enclosed settings that serve to screen (or secure) and cover up, and Blocked Views or those that comprise of superficially blocking components as seen from the onlooker's perspective. The study makes the accompanying decisions about human collaborations and spatial designs: Spacious-Structured classification ought to be preferred the most, and the Open-Undefined and the Blocked perspective classes leaned toward the slightest, with the Enclosed settings reasonably favored dependent upon nature of spatial definition.¹¹⁵

Such evolutionary situations and methodical archetypes have been transferred over to urban settings for similar cognitive studies on environmental perceptions. Two other studies, based on the Kaplans' research, defined spatial configurations in terms of cognitive processes: *Coherence, Complexity, Legibility, and Mystery*.¹¹⁶ In later years and research, these simplified definitions were further expanded to include ratings based on *Spaciousness, Refuge, Enclosure, Coherence, Legibility, Complexity, Mystery, and Typicality*.¹¹⁷

a. Complexity: this quality is defined as a measure for ‘... how much is “going on” in a particular scene, how much there is to look at’.¹¹⁸ A tropical forest often is highly complex, because it contains many different forms, textures, colors, changes in density, and so on (Fig.52). In contrast, a desert contains much less landscape features, and hence, is less complex (Fig.53).

115 Thomas R. Herzog, “A Cognitive Analysis of Preference for Urban Spaces”. *Journal of Environmental Psychology* 12 (1992): 237-48.

116 Roger S. Ulrich, “Natural versus Urban Scenes: Some Psychophysiological Effects”. *Environment and Behavior* 13:5 (1981) 523-56.

117 Thomas R. Herzog, “A Cognitive Analysis of Preference for Urban Spaces”. *Journal of Environmental Psychology* 12 (1992): 237-48.

¹¹⁸ Ibid, 48.

b. Mystery: refers to sites in which the knowledge presented guarantees the individual that more information can be acquired if he or she were to explore the setting in a more thorough fashion. An example of this mystery component in a landscape would be a trail that leads away or a deflected vista (Fig.54).



*Figure 52: Lack of coherence, highly complex setting*¹¹⁹



*Figure 53: Highly coherent, lack of complexity*¹²⁰

¹¹⁹ Rachel Kaplan, Stephen Kaplan, Robert L. Ryan, *With People in Mind: Design and Management of Everyday Nature*. Island Press, 1998.



Figure 54: Vista can provide a sense of mystery, causes viewer exploration¹²¹

c. Coherence: refers to the occurrence of visual cues or qualities that are foundational to the organization, understanding and structuring of the image, such as proportion, patterns, and textures and surfaces. For example, a uniform ground surface can even tie in dissimilar landscape elements together. Trees or tree-groups that have a similar appearance and that are more or less evenly spaced – like in a savanna – can also make a scene more coherent.

d. Legibility: indicates the understanding of places or scenes, and refers to the capacity to expect and sustain alignment in the environment as one further reconnoiters through it. For a quick case illustration, a prominent tree-group or a noticeable rock/hill (Fig.55) could function as a point of orientation.

¹²⁰ Ibid.

¹²¹ Rachel Kaplan, Stephen Kaplan, Robert L. Ryan, *With People in Mind: Design and Management of Everyday Nature*. Island Press, 1998.



Figure 55: Legibility is achieved here, with the rock as a focal point¹²²

The Kaplans additionally propose two cognitive methodologies that confirm visceral reactions to natural settings: Understanding and Exploration. They recommend that first and foremost, the viewer needs to distinguish and have the ability to relate to the image stimuli, and second, the respondents will append themselves to the view or urban setting portrayed in the picture, and may as well need to theoretically investigate past the restrictions observed within the picture.¹²³ One seminal study by Hung et al. investigated this combination of physiological responses and subjective preferences and assigned measures and rating systems to the responses. It was concluded that there was a greater number of people that responded positively to natural rather than urban settings.¹²⁴

Another preference association study amid natural and urban spaces signified that the majority of viewers preferred nature scenes to urban counterparts, and that the least preferred natural setting was still preferred over the most preferred urban setting.¹²⁵ Such studies aid in beginning to distinguish the nature of the visual stimuli presented, and can begin to delineate patterns and correlations among the data, to identify the specific spatial elements and favorable configurations.

¹²² Rachel Kaplan, Stephen Kaplan, Robert L. Ryan, *With People in Mind: Design and Management of Everyday Nature*. Island Press, 1998.

¹²³ Stephen Kaplan, Rachel Kaplan, John S. Wendt, "Rated Preference and Complexity for Natural and Urban Visual Material" *Perception & Psychophysics* 12: 4 (1972) 352-56.

¹²⁴ C.-C. Hung, and C.-Y. Chang, "A Study of the Restorative Effects of Urban and Recreational Settings". *Acta Horticulturae, Horticulture, Human Well-Being and Life Quality*. 639 (2004) 235-39.

¹²⁵ Stephen Kaplan, Rachel Kaplan, John S. Wendt, "Rated Preference and Complexity for Natural and Urban Visual Material" *Perception & Psychophysics* 12: 4 (1972) 352-56.

Habitat and psychoevolution: Kaplans' model

Rachel and Stephen Kaplan improved a qualified data based ecological model, otherwise called the " preference matrix". In this model, mid idea in this structure is 'affect', which is utilized synonymously to the concept 'emotion'. Importantly, Ulrich considered that the quick occurrence of generalized affect constitutes the first level of reaction towards an environment. Such emotional states are basically precognitive and autonomous of distinction. This means that "...we can like something or be afraid of it before we know precisely what it is and perhaps even without knowing what it is".¹²⁶ More importantly, Ulrich's theories of precognition contrast directly with the Kaplans' models of cognitive preferences.

In Ulrich's model, there are two stages of processing, which thus add to the complex interweaving of primary biological reactions with those that are familiar, cultural, or experiential. The brisk onset of such emotional responses is basically adjustable: on the support of almost no informative data the life form is inspired to rapidly undertake activities that commit to its well being and survival. Case in point, if early people ran into a setting holding an imperative danger (e.g. turbulent water), this quickly triggered contrarily toned emotional responses (e.g. hate), eventually expediting evasive conduct. Moreover, if a setting held characteristics that were characteristic of great chances for survival and proliferation (e.g. sustenance), this might have initiated loving responses, which inspired to further explorative conduct. Furthermore, more cognitive evaluations of the environment (recognition, identification and a more detailed processing of the environmental information) can occur following the occurrence of these affective reactions. Significantly, this assessment might be went with by remembrances, nostalgia or familiar associations, which, obviously, could be socially impacted. The aforementioned impact the beginning emotional reaction and simultaneous physiological arousal. Ulrich gives the following example to make his point: "...as an extreme example, an aesthetically spectacular vista would likely elicit an initial affective reaction of strong preference and interest that could sustain a lengthy and elaborated cognitive process, involving detailed perception and processing of the visual information and thoughts as diverse as memories from a childhood vacation or an idea recalled from a poem".¹²⁷

¹²⁶ Roger S. Ulrich, "Natural versus Urban Scenes: Some Psychophysiological Effects". *Environment and Behavior* 13:5 (1981)

¹²⁷ Ibid, 93.

2.4.3 PSYCHOPHYSIOLOGY AND HUMAN RESPONSES

Although psychophysiology, or the “mind-body interaction”, is relatively new as a discipline by itself, the study of human responses and the relationships between psychological changes and corresponding physiological responses has long been practiced around the world for centuries.¹²⁸ Beginning with ancient beliefs and systems of physiology in India and China, to the Greeks and Persians of the relatively modern world, there has been a tremendous interest in the research and practice of psychophysiology. Second-century physicians, researchers, and philosophers as early as Plato have based their systems of understanding through observations and visual determinations of the physiological reactions expressed by subjects to emotional and physical stimuli.¹²⁹

The significance of studying and recording human physiological responses by means of measurable quantities goes beyond qualitative methods such as surveys or questionnaires because physiological responses records human responses before thinking or cognitive level.¹³⁰ It has been shown to be more effective in educating, as well as policy level changes because it is based on medical technologies.¹³¹ Pivotal studies in cognitive perception have been documented since the 1970s. Rachel and Stephen Kaplan's research in environmental psychology supports the importance of assessing human perspectives and reactions. Kaplan et al. studied and assessed human responses to a set of slides depicting different environments and landscapes, and concluded that there are strong differences in the way people respond to natural diversity. Ulrich, through his studies, detailed similar cognitive responses to environmental categories, which were based on years of development of human perceptions to natural and other landscape types.

Heart rate (ECG), skin conductance (GSR), and facial electromyography (EMG) are frequently used to assess the valence and arousal of emotions. Use of skin conductance (GSR) measures arousing and calmness levels a person is experiencing towards a stimulus and is mainly sensitive to the general arousal associated with emotions. For example, in the evaluation of arousal and

128 Robert M. Stern, William J. Ray, Karen S. Quigley., *Psychophysiological recording, Second Edition*. Oxford University Press, Inc., 2001.

129 Ibid, 54.

130 Robert M. Stern, William J. Ray, Karen S. Quigley, *Psychophysiological recording, Second Edition*. Oxford University Press, Inc., 2001.

131 Roger S. Ulrich, “Natural versus Urban Scenes: Some Psychophysiological Effects”. *Environment and Behavior* 13:5 (1981) 523-56.

calmness levels of natural versus urban scenes¹³², incorporated the use of electrocardiograph (ECG) and electroencephalograph (EEG) instruments to measure heart rate and alpha amplitude levels. Specifically, alpha amplitudes were higher when subjects viewed slides with vegetation rather than urban scenes. This is significant since alpha waves are a valid indicator of brain activation and is associated with wakeful relaxation. Furthermore, a trend for higher heart rate activity when subjects viewed slides of water or vegetation was noted. This is important because heart rate is an objective indicator of states of psychophysiological arousal or activation.¹³³

HR DECELERATION: Studies show that decrease in heart rate is a measure of attention, and so a negative change from the baseline (pre-stimulus) indicates that the respondents were paying increased attention to the stimulus.¹³⁴ When experiments were conducted to determine effects of attention on heart rate; it was found that greater heart rate deceleration is associated with highly arousing images and negative images.

HR ACCELERATION: In other studies, heart rate increased more as a response to primal emotions such as anger and fear. Furthermore, elevation in heart rates from the baseline data also indicates that the respondents also recalled specific/associative memories related to the tree images shown, which is indicated by an increase in heart rates.¹³⁵¹³⁶

HEART RATE (ECG) SUMMARY: In general, heart rate deceleration is associated with higher attention levels (orienting response and stimulus intake) and increase in heart rate is related to defensive response and stimulus rejection.¹³⁷

People react differently to designs and ideas, and these differing views can be supported or brought about by various factors—familiarity, cultural background, genetic makeup (instinctual responses), etc.¹³⁸ Correlations have been made among types of environments and people's responses, and these responses can be classified into several different categories based on age,

¹³² Ibid.

¹³³ Roger S. Ulrich, "Natural versus Urban Scenes: Some Psychophysiological Effects". *Environment and Behavior* 13:5 (1981) 555.

¹³⁴ Robert M. Stern, William S. Ray, Karen S. Q., "Psychophysiological Recording". *Oxford University Press* (2001).

¹³⁵ Ibid.

¹³⁶ Roger S. Ulrich, "Natural versus Urban Scenes: Some Psychophysiological Effects". *Environment and Behavior* 13:5 (1981) 523-56.

¹³⁷ Robert M. Stern, William S. Ray, Karen S. Q., "Psychophysiological Recording". *Oxford University Press* (2001).

¹³⁸ Stephen Kaplan, Rachel Kaplan, John S. Wendt, "Rated Preference and Complexity for Natural and Urban Visual Material" *Perception & Psychophysics* 12: 4 (1972) 352-56.

culture, gender, ethnicity and race, etc.¹³⁹, and such classification further helps in understanding the effects of differences in settings on variations in people's cultural backgrounds. The different measures of psychophysiology typically include EEG (Electroencephalography or brain wave functions), ECG (Electrocardiography or heart rate) EMG (Electromyography or muscular activity: corrugator or frown, and zygomatic or smile), and GSR (Galvanic Skin Conductance).¹⁴⁰

This dissertation will incorporate the following FOUR (4) MEASURES:

- A. ECG (heart rate) = Activation levels
- B. EEG (brain's responses) = Wakeful relaxation
- C. EMG (muscular activation) = Smile and frown reflexes
- D. GSR (skin conductance) = Calmness levels

Nature and Human Affective Valence

Research into the affective valence of natural environments mainly deliberates on their possible 'restorative' potential for human individuals. This recuperative characteristic is the principal role played by nature and natural settings in investigation of human physiological responses that are non-aesthetic. The following pages discuss this relationship between nature and stress reduction in humans, as has been studied over time.

Nature and Restorative Values: Non-stressed respondents

Stress-reducing effect of nature is still effective today because those individuals that could respond restoratively to stressful situations survived better.

Roger Ulrich studied the effects of different classes of environments on the psycho-physiological states of individuals. These environments were displayed to the subjects on slides and were 'nature with a water feature', 'nature dominated by vegetation', and 'urban environments without water features or vegetation'.¹⁴¹ Before and after viewing each environmental category, subjects had to rate their feelings according to two types of psychological measures. The first measure was

¹³⁹ Roger S. Ulrich, "Natural versus Urban Scenes: Some Psychophysiological Effects". *Environment and Behavior* 13:5 (1981) 523-56.

¹⁴⁰ Thomas R. Herzog, "A Cognitive Analysis of Preference for Urban Spaces". *Journal of Environmental Psychology* 12 (1992): 237-48.

¹⁴¹ Roger S. Ulrich, "Natural versus Urban Scenes: Some Psychophysiological Effects". *Environment and Behavior* 13:5 (1981).

a (semantic) questionnaire assessing the feelings and mood of the subjects during the test. The second measure was a Zuckerman Inventory of Personal Reactions (ZIPERS). This is an instrument that determines how subjects feel with regard to five affective states: fear arousal, positive affect, anger/aggression, attentiveness and sadness. For each item subjects give a score, ranging from 1 (very little) to 5 (very much), and this indicates the degree to which the affective state applies to the subject's current mood.

Additionally, two types of physiological variables were measured before, during and after this experiment: 1) Brain waves (EEG) and 2) Heart rate (ECG). First, by measuring the electrical activity in the brain, the alpha amplitude was registered, which correlates with states of consciousness and alertness. High alpha amplitudes correspond with lower levels of physiological arousal, and low alpha is an indication of higher arousal. The second physiological parameter was heart rate. Generally, an increase in heart rate correlates with higher arousal.

The ZIPERS and the semantic survey uncovered that vegetation, and particularly water characteristics, had a positive impact on the subjects' temperament and sentiments. Comparative effects were gotten for the physiological tests: alpha amplitudes had a tendency to be higher while review vegetation, instead of urban scenes. This shows that subjects felt more calm and relaxed in the previous condition. Ulrich accepts that the aforementioned discoveries are concurrent with view that nature scenes are more fruitful in inspiring arousal and thoughtful, contemplative consideration.

Nature and Restorative Values: Stressed respondents

Ulrich et al. have also studied the effects of nature versus urban views on stressed individuals. The study consisted of two phases: 1) Stressor, and 2) Recovery. During the implementation of the first phase, subjects were confronted with a stressor. The participants were shown a video about the prevention of working accidents, showing injuries, blood, and mutilation. During the recovery phase, shortly after exposure to this stressor, subjects viewed videos of natural and urban settings.¹⁴² The goal of this experiment was to determine the stress reducing effect of

¹⁴² Ulrich, R.S., Simons, R.F., Losito, B.D., Fiorito, E., Miles, M.A. & Zelson, M. "Stress recovery during exposure to natural and urban environments". *Journal of Environmental Psychology*, (1991), 11, 201-230.

natural elements on stressed individuals, and to see whether urban settings would hamper such recuperation.

For this experiment, the psychological measure also implemented ZIPERS, recorded before and after the stressor was administered, and after the recovery tape was played to each respondent. Physiological measures were then continuously recorded during the stressor and the environmental tapes. The experiment methodology involved recording the ECG (electrocardiogram), PTT (pulse transit time), SCR (skin conductance response), and EMG (electromyogram). During exposure to stressful situations, EMG and SCR increase, and these same measures decrease during recovery. On the other hand, PTT decreases during stress, while it increases during recovery. Although it is seen that the relation between heart rate and stress is not as readily apparent or understood thoroughly, it was discovered that changes in heart rate depended on the features of the stressor. If the stressor involved problem solving, or the manipulation, storage and retrieval of information, then heart rate increases. If a certain stimulus elicits intake, attention/interest, then heart rate decreases.

Investigations demonstrated that the avoidance tape was fruitful in inspiring both mental and physiological anxiety. Estimation of three physiological variables (PTT, SCR and EMG) throughout the recuperation stage uncovered a speedier and more complete anxiety recuperation when subjects were faced with nature-based, rather than urban sceneries. As to heart period, there was a deceleration on account of nature sceneries and increasing speed for urban situations. Ulrich et al. inferred that comprehension and attentive capabilities were higher when subjects saw nature scenes, than when they saw urban situations.¹⁴³ Respondents or participants that were exposed to nature views scored lower for the factors Anger/Aggression and Fear, and reported higher levels of Positive Affects. In addition, influence of nature on feelings of Sadness and on Attentiveness/Interest was found to be statistically insignificant.

Thus, it is clearly evident that natural settings, as opposed to urban environments, have a more positive influence on subjects' psychological and physiological states, and lead to higher levels of attention and intake.

¹⁴³ Ulrich, R.S., Simons, R.F., Losito, B.D., Fiorito, E., Miles, M.A. & Zelson, M. "Stress recovery during exposure to natural and urban environments". *Journal of Environmental Psychology*, (1991), 11, 201-230.

Attention Restoration Theory (ART)

An additional part of restoration proposed by Stephen and Rachel Kaplan illustrates that helpful encounters intimate the recuperation of the ability to 'direct attention' or to 'focus'. As per the Kaplans, such situations have four propeties.¹⁴⁴ To start with, helpful situations inspire 'fascination'. Interest is easy and automatic, and along these lines permits the voluntary or administered thoughtfulness regarding rest. A second property is 'being away' or liberating oneself from the sources that are requesting for one's guided consideration. Third, the therapeutic environment might as well have 'extent', which implies that it must be rich and rational enough to keep a person intrigued and entranced, i.e. to keep the psyche occupied. Fourth, there must be "similarity" between the remedial environment and one's purposes and inclinations. What one might want to do and what one is attempting to do ought to be in close agreement with the aspects of the setting. This intimates that no consideration ought to be paid to if one's conduct is fitting for nature's settings. Nature nearly meets the previously stated restoration hypothesis, and is thusly particularly adequate in resting attention and focus in a directed manner.

Other basal empirical findings lend credence to the theory of nature and its restorative potential of natural settings on humans. Hartig et al. conducted two related studies that proved this theory and took it a step further. In these experiments, individuals were divided into two groups, depending on their choice of holiday destination. The respondents who chose 'free' nature scored better in some attentive tasks such as proofreading, while those who went away on a 'city' holiday scored much lower on the tests.

Nature and Cognition

There is some another validated study which proves that the presence of vegetative components is likewise invaluable for cognitive working. Lohr et al. uncovered through studies that subjects felt more thoughtful and attentive when they had performed a test in a room with plants, contrasted with subjects that made the test where plants were absent or removed. Moreover, response times in the test were 12% quicker in the planted condition than in the no-plant condition. This shows that the existence and growth of plants can emphatically impact profit.¹⁴⁵

¹⁴⁴ Kaplan, R. & Kaplan, S. (1989), *The Experience of Nature: A Psychological Perspective*. Cambridge: Cambridge University Press.

¹⁴⁵ Lohr, V.I., Pearson-Mims, C.H. & Goodwin, G.K., "Interior plants may improve worker productivity and reduce stress in a windowless environment." *Journal of Environmental Horticulture*, (1996) 14, 97-100.

In a specific public housing setting, a study was conducted to correlate the crime rates against landscaped areas by Kuo and Sullivan. The amount of greenery outside the apartments varies considerably: from completely barren, small trees and grass, to high-canopy trees. The researchers observed that “..compared to buildings with low levels of vegetation, those with medium levels had 42% fewer total crimes, 40% fewer property crimes, and 44% fewer violent crimes.. Buildings with high levels of vegetation had 52% fewer total crimes, 48% fewer property crimes, and 56% fewer violent crimes than buildings with low levels of vegetation”.¹⁴⁶

Physiological Measures of Analysis: ECG, EEG, EMG, and GSR

As previously discussed, different physiology measures typically include ECG (Electrocardiography or heart rate), EEG (Electroencephalography or brain wave functions), EMG (Electromyography or muscular activity: corrugator or frown, and zygomatic or “Smile”), and GSR (Galvanic Skin Conductance). First, a baseline series of data waveforms is established where the respondent is instructed to relax and a blank slide is introduced for sometime (typically for about 30 seconds to a minute in length). Psychological stimuli and corresponding physiological responses have been construed to involve a combination set of responses. Complex reactions are thereafter studied in relation to each other before basing results and discussions regarding the available data sets. Additional “noise” could be generated due to stress levels, fatigue, and extraneous distractions, thereby resulting in recording of unwanted data. Precautions and proper set up measures should be taken to ensure that these factors are observed and recorded during the course of the experiment, and filtered during data analysis.¹⁴⁷ Responses are finally measured, contrasted, and analyzed to identify states, and perceptual reactions to the stimuli that are presented. Some measurement factors and states include *Alertness*, *Wakefulness*, and *Arousal*.¹⁴⁸

¹⁴⁶ Kuo, F.E. & Sullivan, W.C. Environment and crime in the inner city: Does vegetation reduce crime? “Environment & Behavior, (2001) 33, 343-367.

¹⁴⁷ Stern, Robert M., William J. Ray, Karen S. Quigley. *Psychophysiological recording, Second Edition*. Oxford University Press, Inc., 2001, 35.

¹⁴⁸ Roger S. Ulrich, “Natural versus Urban Scenes: Some Psychophysiological Effects”. *Environment and Behavior* 13:5 (1981)

2.4.4 BIOPHILIC DESIGN

Biophilia: Environmental Ethics and Empirical Studies

Ulrich also proposed that the basis for biophilia is that when people possess inborn negative reactions to certain natural stimuli, then it isn't too hard to suppose that positive reactions to them – which are claimed to guide adaptive behaviors – also have a partly genetic basis: 'A general argument ... is that theoretical propositions for an innate predisposition for biophilia gain plausibility and consistency if they also postulate a corresponding genetic predisposition for adaptive biophobic responses to certain natural stimuli that presumably have constituted survival related threats throughout human evolution'.¹⁴⁹ Stephen Kellert argues that biophilia depends on interplay of nine specific values (Fig.56). According to Kellert, these '... represent a basic human relationship and dependence on nature indicating some measure of adaptation value in the struggle to survive and, perhaps more important, to thrive and attain individual fulfillment'.¹⁵⁰ According to Edward O. Wilson: '[t]he biophilia hypothesis ... hold[s] that the multiple strands of emotional response are woven into symbols composing a large part of culture'.¹⁵¹ This is clearly visible in architectural design, where aesthetic enhancements often draw inspiration from natural forms and entities.

Biophilic design process

Stephen Kellert also argues that Biophilia and its effects on the methodologies concerning creative designing and place-making had the following characteristics: "...the aesthetics of nature can function as a kind of monumental design model. These environmental attributes suggest proven pathways of success in a multiplicity of shapes and forms. By discerning beauty and harmony in the natural world, we advance the belief and sometimes the understanding of how certain configurations of line, space, texture, light, contrast, movement, prospect, and color may be employed to produce analogous results in the human experience".¹⁵² Furthermore, to make connections between neuroscience and architectural theories, Nikos Salingaros claims that there is an important '... resemblance between minimalist or disordered built environments, and the perception of a normal, visually complex environment by persons with a damaged perceptual

¹⁴⁹ Ulrich, R.S., "Biophilia, Biophobia, and Natural Landscapes", In Kellert, S.R. & Wilson, E.O.(eds.), *The Biophilia Hypothesis*. Washington: Island Press, (1993) 75.

¹⁵⁰ Kellert, S., "The biological basis for human values of nature". In Kellert, S.R. & Wilson, E.O. (eds.), *The Biophilia Hypothesis*. Washington: Island Press, (1993) 58.

¹⁵¹ Wilson, E.O. "Biophilia and the conservation ethic". In Kellert, S.R. & Wilson, E.O. (eds.), *The Biophilia Hypothesis*. Washington: Island Press, (1993) 31.

¹⁵² Kellert, S., "The biological basis for human values of nature". In Kellert, S.R. & Wilson, E.O. (eds.), *The Biophilia Hypothesis*. Washington: Island Press, (1993) 61.

apparatus ... different types of injury to the eye and brain result in precisely the same effects offered by either minimalist or intentionally disordered design'.¹⁵³ Ulrich suggests that most modern built environments lack natural characteristics, "...they lack the icons of habitability", or what he terms "environmental preferenda" and that exposure to such environments could rapidly and automatically trigger negatively toned feelings.¹⁵⁴

	<i>Biophilic value</i>	<i>Adaptive value</i>
Utilitarian	The material value of nature.	This value helps to get physical sustenance, security and protection. Think for example of plants as a source of food and medicine.
Naturalistic	Fascination, awe and wonder about nature, which triggers curiosity and exploration.	This value leads to increased knowledge and understanding of nature, and is beneficial for physical fitness, and outdoor skills.
Ecologistic-scientific	The systematic study of structure, function and relationships in nature.	Those who could precisely observe, analyze and study in detail the richness of life-forms had a clear survival advantage.
Aesthetic	The aesthetic impact of nature on individuals.	This value provides a guide for finding food and safety.
Symbolic	The symbolic value of nature is perhaps most prominent in language, where metaphors and symbols referring to the natural world are omnipresent.	Symbolizations and metaphors facilitate communication, thinking and mental development.
Humanistic	The deep emotional bonds that an individual can develop with (elements of) the natural world. Perhaps this 'love for nature' is most pronounced in the human relationship with domesticated animals.	Human-animal relations can function as a template for bonding, altruism and sharing - values important for social beings like humans. Bonding with companion animals is also important because these can help in finding food and can offer protection. Furthermore, by mimicking the behaviour of (semi)domesticated animals, one can get more adapted and attuned to the environmental context.
Moralistic	The '... strong feelings of affinity, ethical responsibility, and even reverence for the natural world' (Kellert, 1993, 53). Often, this goes hand in hand with attributing nature a spiritual meaning	This value can contribute to feelings of kinship, affiliation and loyalty, which in turn can promote cooperative and altruistic behaviour. Furthermore, projecting intrinsic meaning and ordering onto the cosmos can lead to more conservationist attitudes towards the natural environment and might also enhance feelings of wellbeing.
Dominionistic	The wish to master, to physically control, and to dominate the natural world.	Such stances can lead to increased knowledge and understanding of the natural world, and might improve mechanical skills and physical prowess.
Negativistic	Contact with nature is not always a pleasant experience, but can also be associated with fearful or even phobic responses.	Such behaviour motivates the individual to search for security, protection and safety.

Figure 56: Kellert's Nine (9) biophilic values¹⁵⁵

¹⁵³ Salingaros, N.A., "The sensory value of ornament". Communication & Cognition, (2003) 36, 332.

¹⁵⁴ Ulrich, R.S., "Biophilia, Biophobia, and Natural Landscapes", In Kellert, S.R. & Wilson, E.O.(eds.), The Biophilia Hypothesis. Washington: Island Press, (1993), 79.

¹⁵⁵ Kellert, S., "The biological basis for human values of nature". In Kellert, S.R. & Wilson, E.O. (eds.), The Biophilia Hypothesis.

Biophilic design Forms: Geons, Curves, and Organics

It is quite evident that case studies of 'biophilic architecture' still point symbolically to nature. Be that as it may the characteristic shape experiences truly some amount of abstraction, while offering a few prominent perceptual similitudes to true common components. For instance, in Santiago Calatrava's Quadracci Pavilion there is still an apparent similarity with a winged animal's wings. Perhaps it is conceivable to leave mere representation generally behind, while the building structure holds some of its instinctive nature by joining certain shape primitives (Fig.57) that are just slightly evocative of their natural originals; this lack of evocation may often be almost considered irreverent to the design process.

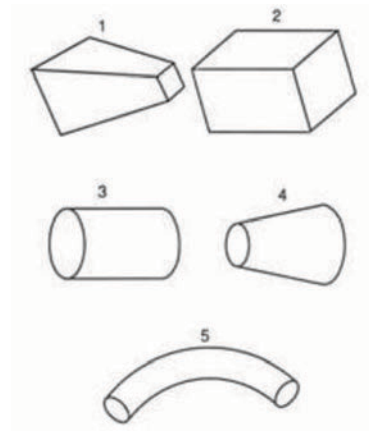


Figure 57: Perceptual “form primitives” extracted from natural forms

On the other hand, there has been various studies and research on the relation between positive affect and curved forms and surfaces. Although intuitive and non-empirical, Kellert theorizes that: “...symbolic designs of nature [like curved shapes] occur throughout human history and across all cultures, though perhaps less so in modern, urban society. The ubiquity of these environmental simulations reflects a universal yearning often incorporated into building interiors and sometimes into exterior landscapes”.¹⁵⁶

To assimilate evidence-based exploration or experimental confirmation, Nancy Aiken (1998b) has contended that certain straight examples can function as a "releaser" of full of feeling reactions, and notes how the aforementioned are regularly utilized within architectural detailing or craftsmanship. The idea "releaser" is fundamental to alleged 'releaser-response bundles'. The aforementioned are units of natural reflexive conduct, comprising of three imperative parts: a (1)

Washington: Island Press, (1993) 58.

¹⁵⁶ Kellert, S. Building for Life: Understanding and Designing the Human-Nature Connection. Washington: Island Press. (2005).

stimulus or "releaser" that can trigger a (2) appropriately placed neural instrument, which accelerates a specific (3) adaptively behavioral characteristic or response. Early investigations of indicated that subjects needed to copartner diverse sorts of lines with different full of feeling descriptive words (e.g. 'sad', 'quiet', 'furious', 'harsh', et cetera).¹⁵⁷ The aforementioned trials uncovered that straight or angled lines and forms were releasers of distinctive classifications of feeling tones. It was discovered that straight forms were prevalently connected with hostile attributes, while curved lines and forms were correlated with "affiliative" aspects. Vantage point outlook as observed from a psychoevolutionary standpoint seem to indicate an absence of theories to suggest an inherent affinity for curved forms; however, it is also true that it is the tangible absence of angled lines or sharp objects that leads to positive valences or responses from humans, when presented with non-linear shapes, forms, and architectural designs. This absence gets the respondents to sense and feel a measure of comfort within completely natural settings. Curved objects and forms in the built environments also reflect an inborn predilection for natural-like forms and patterns. Bell, in his study, observes that: "...spirals occur in nature, meanders in rivers – do these signify life forces when used as decoration? We will never know for certain, but it is significant, in our quest for patterns, that so many natural ones have a strong attraction to us".¹⁵⁸ A decidedly agreeable theory by Salingaros states that curves are higher in information content, and thereby respond to our need for moderately complex information¹⁵⁹ (Fig.58).

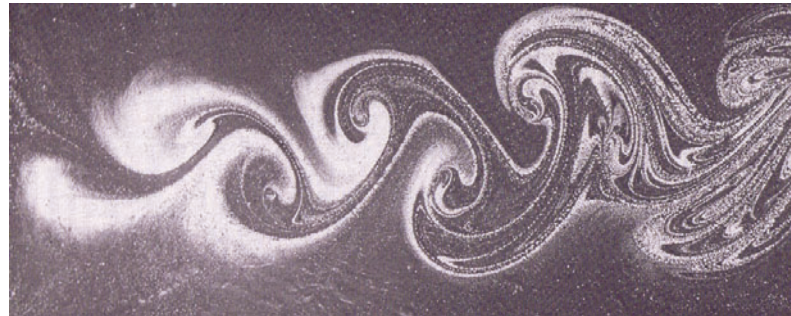


Figure 58: Train of vortices produced by a brush drawn in a straight line through standing water.¹⁶⁰

With regards to organic architecture, the free form seems to originate from this blatant rejection of the straight angle or line, and is expressed by a keen utilization of curved surfaces.

¹⁵⁷ Aiken, N.E., "The biological origins of art". Westport: Praeger (1998).

¹⁵⁸ Bell, S., "Landscape. Pattern, Perception and Process." London: E & FN Spon Press (1997), 37.

¹⁵⁹ Salingaros, N.A., "The sensory value of ornament". *Communication & Cognition*, (2003) 36, 332.

¹⁶⁰ Ibid.

Upon observation of architectural works by Louis Sullivan and Frank Lloyd Wright (Fallingwater, for example), it leads one to believe that free-form styles and building design seems to form a recurring pattern of expression to express organic architecture. The works formed during the 'Art Nouveau movement' also inferred response to nature, which fundamentally brought about an investment for botanical or organic elements and forms that were chiefly connected to the building work (i.e. as decoration). Conversely, in 'expressionist architecture', biomorphism is often a standard of normalcy while design and characterizing built environments, and is substantially much more derived from natural organisms and entities (Fig.59).

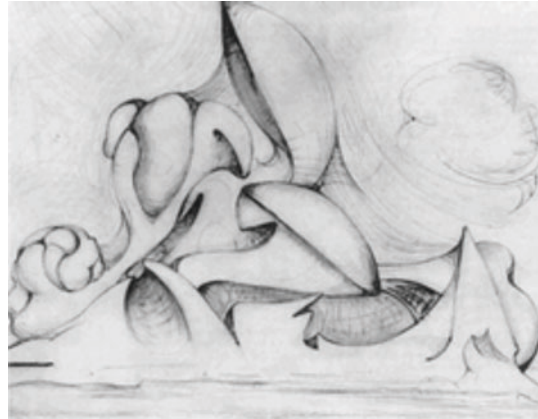


Figure 59: Expressionist architecture: one of Hermann Finsterlin's biomorphic designs

PART 3

Methodology

3.1 ECO OFFICE: SITE AND CONTEXT

The site chosen is within Honolulu, where the building design capabilities will be allowed to stretch beyond the normal limits of sustainability; and where the structure functions as a commercial office space on Ala Moana Boulevard (Fig.59), as well as a model of the urban character within the Hawaiian islands.



Figure 60: (Top to Bottom). Site context and design setting.

3.2 ECO OFFICE: DESIGN PROGRAM

- Site is situated along the waterfront = principles of biomimicry have been limited to the study of a LEAF, located in a plant systemic context.
- The design and scope of this thesis, and of the ‘ECO OFFICE’ will be particular to the tropics and the subtropics, for context and relevance.

The following design programs have established the scope and characteristics of the ECO OFFICE on Ala Moana Blvd.

1. A 5,000 sft. office space (that follows the design of the proposed master plan area).
2. The ECO OFFICE implements in detail the following strategies (using a mix of biomimetic and nano architectural strategies):
 - a. Regulation of light through building façade’s design module
 - b. Regulation of wind through building façade’s design module
3. The ECO OFFICE implements design strategies that result in overall best practices for HUMAN COMFORT (environmental and visual).
4. The ECO OFFICE dictates a set of post-experimental design analyses on psychophysiological testing and responses to the biomimetic and nano architectural concepts.

3.3 STUDY PROTOCOLS AND METHODS

The methodology for the dissertation is implemented in three sections. The hypothesis of this research is that there are some specific nature-based architectural cues that can be incorporated in building technologies. If these particular elements are delineated, then they could be designed, through a combination of interactive design concepts and incorporation of effectively designed elements to create responsive concepts in architectural sustainability; this research was focused on subtropical architecture, specifically within Honolulu, Hawai'i.

3.3.1 'BIOMORPHISM' METHODS

The first section, *Biomorphism*, sought to research and investigate the concepts of biomimicry, while seeking inspiration from natural systems and organisms to incorporate design module strategies in a built environment; this involved creation of three (3) design module prototypes incorporating the most effective building envelope strategies for the 'ECO OFFICE'.

The TREE \leftrightarrow LEAF Analogy

An essential intent of this final project is to experiment with various dynamic relationships, as seen in nature. The TREE \leftrightarrow LEAF relationship and interactions as applied to the design are explored in this research, and the design and implementation explained (and expressed) in detail, in the implementation and analysis section.



Figure 61: Form investigations for the design module

Several shapes, forms, and configuration characteristics were explored in detail; finally, there were three Design Modules (Figs. 59, 60):

- 1) RECTANGLE form (dynamism in ANGLE): Responsive to WIND PATTERN/ Air
- 2) ORGANIC form (dynamism in POROSITY): Responsive to SUN PATH/ Light

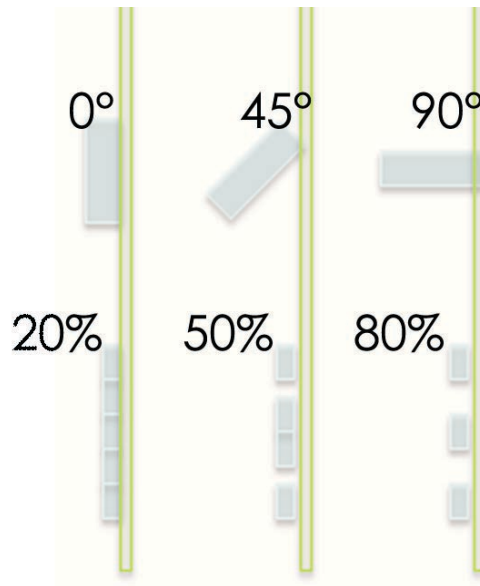


Figure 62: Morphology investigations: design modules (Top: ANGLE, Bottom: POROSITY)

Façade Module Interactive Concepts

The design process and methodology within this Biomorphism phase of the dissertation involved conceptualization of the following ideas:

- 1) Combination of different strategies together to effectively realize the concept of a truly dynamic building skin that would respond to solar and wind patterns.
- 2) Micro and macro changes in the design modules would also be an interesting addition to the interactive and didactic aspects of the building skins.

Building Façade Surfaces

RECTANGLE Module: A basic rectangular grid to initialize my dynamic surface, responsive to the SUN PATH.

ORGANIC: A static, curvilinear surface for the responses generated to the WIND PATTERN.

3.3.2 ‘BIOMIMICRY’ METHODS

The second section, *Biomimicry*, looked at biomimetic research, with particular attention focused specifically on the “materials” and “processes”. “Materials” involved exploration of nanotechnologies best applicable to building façades and envelopes in the ‘ECO OFFICE’; this section also looked at “Processes”, which involved the integration of the selected biomimetic and nano-systems with architectural design, while “testing” the passive design efficiency of the prototype using simulation studies to determine DAYLIGHTING, VENTILATION, and THERMAL COMFORT (Revit, Ecotect and Autocad) to determine the efficiency and applicability of these design module systems.

Nanotechnologies (MATERIALS)

How can we employ biomimicry (nature-inspired concepts) in nanotechnology research, in order to maximize building energy input/output in terms of daylighting, ventilation, and thermal comfort in the tropics? Janine Benyus, co-founder of the Biomimicry Guild, mentions in her book ‘*Biomimicry: Innovation Inspired by Nature*’, there are two approaches for using biomimicry: -

- a) In the **biology-to-design** approach, a biological phenomenon suggests a new way to solve a human design challenge.
- b) In the **design-to-biology** approach, the innovator starts with a human design challenge, identifies the core function, and then reviews how various organisms or ecosystems are achieving that function.

The aforementioned elements and related functions were limited to the study of the site as a physical/environmental context, in relation to the **biomimetic processes of a LEAF**, located in said context **of a PLANT/ TREE**. The design and scope of this thesis, and of ‘ECO OFFICE’ did not seek to incorporate principles mimicking/emulating organisms irrelevant to the site, and the “lifecycle” analysis will be particular to the tropics and the subtropics, for relevance.

Base Model

Three (3) key strategies were explored and realized, whilst keeping the site and the building design of ‘THE ECO OFFICE’ (Figs. 61, 62, 63) in context:

- a. Light Transfer
- b. Air Transfer
- c. Heat Transfer

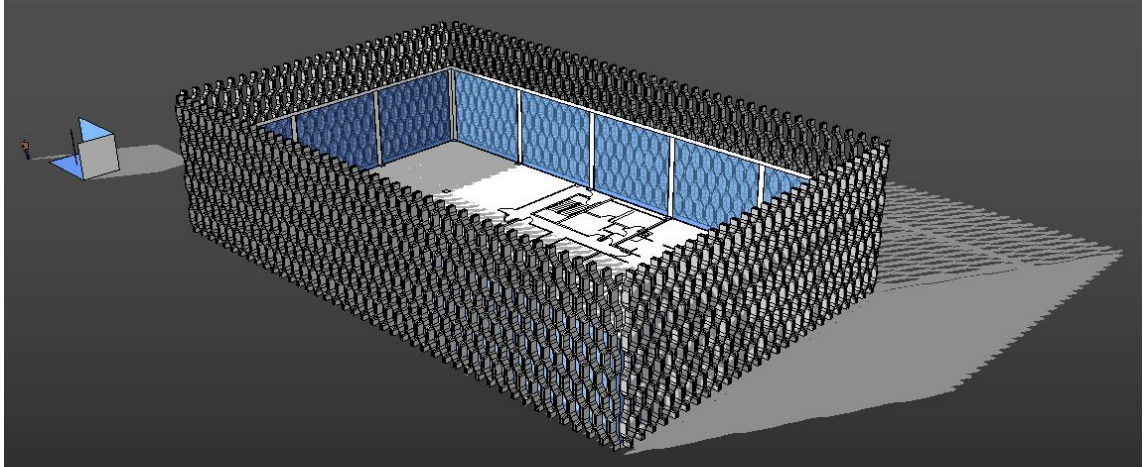


Figure 63: Base design model of the 5th floor plan IBM building

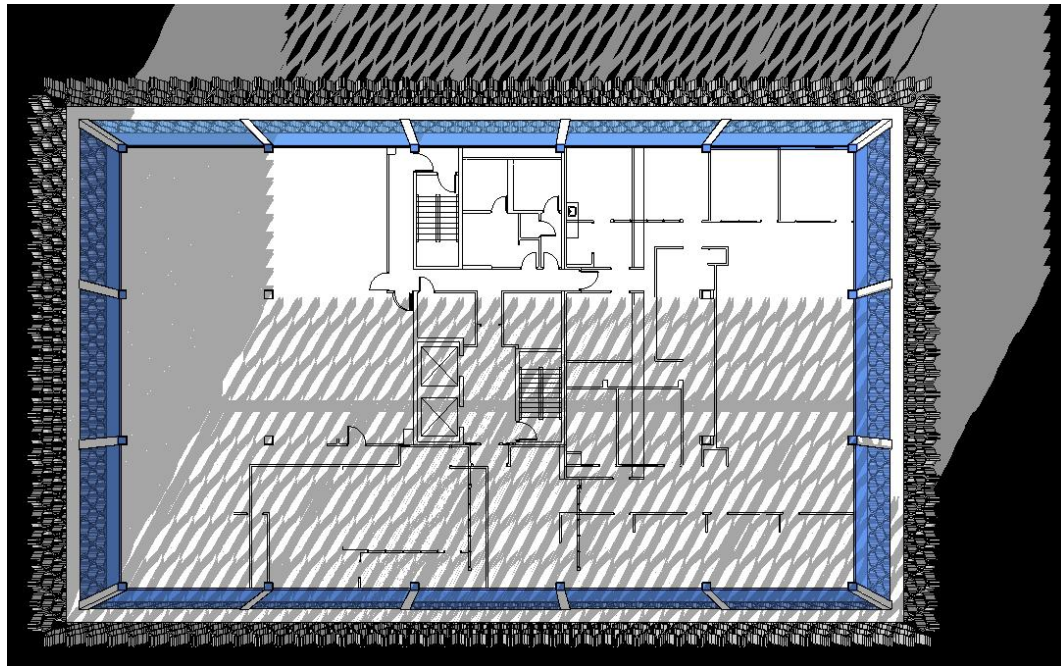


Figure 64: Base design model of the 5th floor plan IBM building: Plan

The site chosen was relatively simple; and the materials used for the base model were:

- 1) Glass (single glazing) for wall space, 2) Concrete (stucco finish) shading fins or brise soleil,
- 3) Suspended ceiling finish, 4) Concrete floor slab

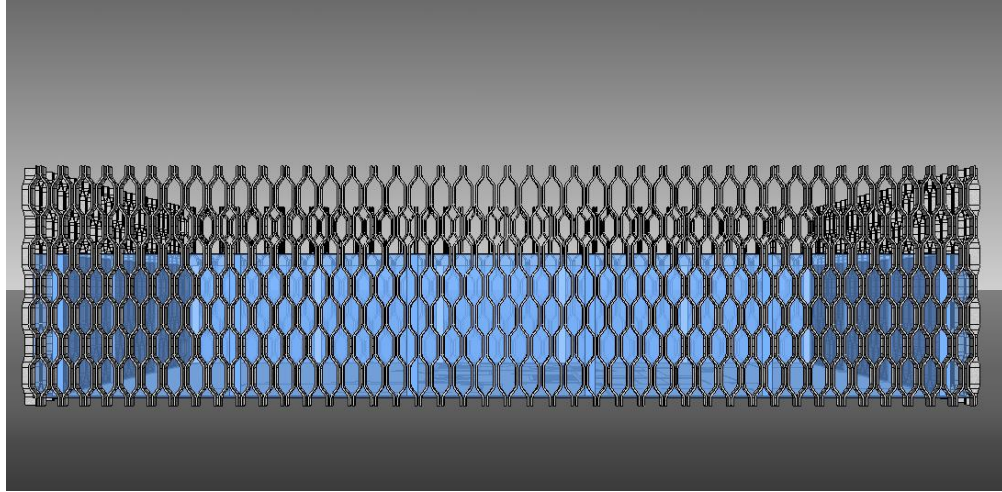


Figure 65: 5th floor plan IBM building: Front (southern) façade.

Four (4) Key Design Modules

[O]: BASE Module (as it is): Single glazing with brise soleil

[A]: RECTANGULAR design modules, ANGLE change responses to LIGHT changes

[B]: ORGANIC design modules, POROSITY change responses to AIR changes

[AB]: HYBRID design modules, ANGLE & POROSITY change responses to LIGHT & AIR changes

Software Simulations

By utilizing software simulations (Ecotect ---→ SketchUp ---→ Rhino ---→ Revit ---→ Autocad), analysis was performed on the different design modules (O = Base, A = Rectangular, B = Organic, and AB = Hybrid). The initial models were built in Sketchup and Rhino, and then transferred into Ecotect and Revit, in order to perform calculated analysis of the following measures:

- a. Light Transfer [Daylighting levels in “lux” units]
- b. Air Transfer [Interior wind speeds in “m/s” units, and cell pressures in “Pa” (pascal) units]
- c. Heat Transfer [Thermal Comfort measured using heat gain indices, Internal Temperature assessments in deg. C)

3.3.3 ‘BIOPHILIA’ METHODS

The third and final section, *Biophilia*, of this dissertation involved a random selection of the Honolulu population to be respondents for the experiment, and then recording their physiological responses based on their reaction to the ‘ECO OFFICE’ façade design images shown.

Study phases involved in Biophilia analysis

- Setting up and calibrating psychophysiology instruments
- Testing of stimulus
- Respondent sampling
- Administering stimulus to respondents
- Analyzing data
- Writing up results
- Publication and dissemination of findings

Respondent Sampling

Respondents/participants comprised of international graduate students and researchers from the University of Hawai‘i campuses, and within the island of O‘ahu. A total of 40 respondents were brought in through various means (flyers/posters, word-of-mouth, class signups, e-mail listservs), and from differing disciplines and interests/fields of study. The respondents also belonged to different cultural backgrounds with a majority from the following ethnicities: Asian, Caucasian, Native Hawai‘ian, and multi-ethnic.

Also, the consistency within the images and the standard quality of the stimuli were factors ensured to maintain objectivity among the respondents, irrespective of cultural or educational bias.

Stimulus Testing

Twelve (12) total images were prepared for the experiment in random order, consisting of 3 trials. Each visual image (stimulus viewing time 10 seconds) was followed by a corresponding blank slide for a slightly shorter time period (6 seconds). Therefore, the time between slides (stimuli) was 16 seconds. Participants were seated comfortably, and the researchers made sure that the electrodes (non-invasive dermal sensors) used for testing were in working condition, and that there were no extraneous signals or noise.

The author/researcher looked at studies based on visual perception and cognition (refer to literature review on Biophilia), and determined the characteristics that would be involved in the dissertation study such as reducing the complexity within the imagery so as to avoid distraction, image quality of the stimuli to be presented, and clarity of content. A few independent researchers and professionals (not involved with this study) were asked for opinions and the stimuli were modified based on suggestions received.

Physiological measures: Experimental (laboratory) settings

The premise of the study (incorporating psychophysiological feedback as analysis tools) was to assess and analyze the responses of people to the functions and aesthetics of the architectural designs (proposed building façade design modules). The psychophysiological experimental set up involved a random selection of the Honolulu population to be respondents for the experiment, and then recording their physiological responses based on their reaction to the building's design module images shown.

Respondents were seated in a room (viewing area) in a landscape laboratory within the University of Hawai'i at Manoa campus, and were shown images of different image simulations and building environments (of the Principal Investigator (P.I.)'s proposed architectural design modules) on a 63.5cm video monitor. During the viewing of these building images, psychophysiological measurements were recorded using non-invasive dermal sensors. These sensor measurements/responses were received, processed and recorded through a Biopac MP-150 psychophysiology measuring system, which were then converted into digital responses and computerized by Acqknowledge 4.2 software, on a Windows XP Professional desktop computer. The stimuli were run and presented using Medialab stimulus presentation software, run by Windows XP Professional desktop computer. The total viewing time was approximately 15-25 minutes, for each respondent.

The dissertation's experimental setup for the physiological analysis incorporated the following four (4) measures (Fig.66):

1. ECG (heart rate) = Activation levels
2. EEG (brain's responses) = Wakeful relaxation
3. EMG (muscular activation) = Smile and frown reflexes
4. GSR (skin conductance) = Calmness levels

Finally, these responses were recorded, studied, and analyzed to figure out patterns and elements of interest; experimental methods were also supplemented with subjective reasoning behind the respondents' reactions and/or verbal responses provided in the accompanying survey questionnaires.

Psychophysiology and Statistical analysis

To understand the relative importance of these verbal and written responses, they were augmented in the other procedure prior to utilizing questionnaires, in which the respondents were tested for their change in physiological responses to the images shown of the trees in Hawai'i.

Statistical analysis was conducted on the physiological waveform (response) data from the lab experiment data.

1. A mixed-model ANOVA (SAS) was used.
2. A repeated measures statement was included, owing to repeated measures taken per subject.
3. Dependent variables were designated and the analyses run individually, with the "ModuleTYP" as the independent variable.
4. The "Tukey-Kramer" test was applied for pairwise separation of means following significant ANOVA.

Decades earlier, when the study and recording of psychophysiology was relatively new, primitive controls and measures had to be adopted in order to effectively document a human physiological response. To make the recording real-time and valid for understanding, several hours were spent in conducting the experiment and establishing baseline data for reference. These methods resulted in longer study periods and caused habituation (or lack of response followed by a series of similarly presented visual stimuli). Recent methods and instruments along with use of computers have been proven to be much more sensitive and faster at processing data real-time. Also, statistical analysis is easier with the use of efficient software input.

SAS software was used with a mixed-model ANOVA followed by the Tukey-Kramer test to separate means. A repeated measures statement was included in the SAS MIXED model, to account for repeated measures on each subject.



Figure 66: Biopac (Example) Acqknowledge 4.1 software waveforms, UH Manoa CTAHR lab.

Respondent Sub-groups: X and Y

The forty (40) total respondents were equally divided into two sub-groups: X (control) and Y (experimental).

Group X: This sub-group consisted 20 respondents (10 male, 10 female), who were part of the “control group”. These respondents were led into the experimental and testing procedure and protocol without any prior knowledge about the variables that went into the design process.

Group Y: This sub-group also consisted similar 20 respondents (10 male, 10 female), who were part of the “experimental group”. These respondents were led into the experimental and testing procedure and protocol and were briefed, prior to the experiment, about the researcher/ author/ experimenter’s design process and dissertation hypotheses. Also, the respondents in Group Y were informed about the intentions of the psychophysiological study, i.e., to assess human affective responses to Biomorphic, Biomimetic, and Biophilic designs.

Psychological responses: Survey questionnaires

After images were shown and biofeedback responses recorded, a questionnaire based on the images that were shown were given to each respondents to fill out and complete (this took 5- 10 minutes). This second part of the testing methodology used questionnaire data, post-stimulus recordings, with each respondent, based on responses to determine which images within the

stimuli they preferred and their reasons why. The questionnaires were anonymous, simple, easy-to-use, and consisted of questions that did not pose any ambiguity. Respondents were asked what and why their preferences for the visual stimuli were, and were also questioned about their educational and professional interests/background. The questionnaire also had some info to be filled in by the respondents regarding their age group, gender, and cultural background, in order for the researchers to determine any factors/influences relating to their particular responses.

Later, these responses were recorded, studied, and analyzed to figure out patterns and elements of interest, and also supplemented with reasons behind the respondents' reactions and/or verbal responses provided in the accompanying questionnaires.

The two parts are correlated to determine the actual response to the images presented, with a clear determination of the reasoning behind these reactions and responses.

PART 4

Design Implementation and Analysis

4.1 BIOMORPHISM: Analysis and Discussion

Design Modules: Translation from TREE <-----> LEAF analogy

First, a number of design modules, that would effectively source the translation from the “leaf” to building façade, were explored (Fig.67). Next, the design process involved the possibility of dynamism within the modules, and strategies on how to build them in the simulated models and scripts.

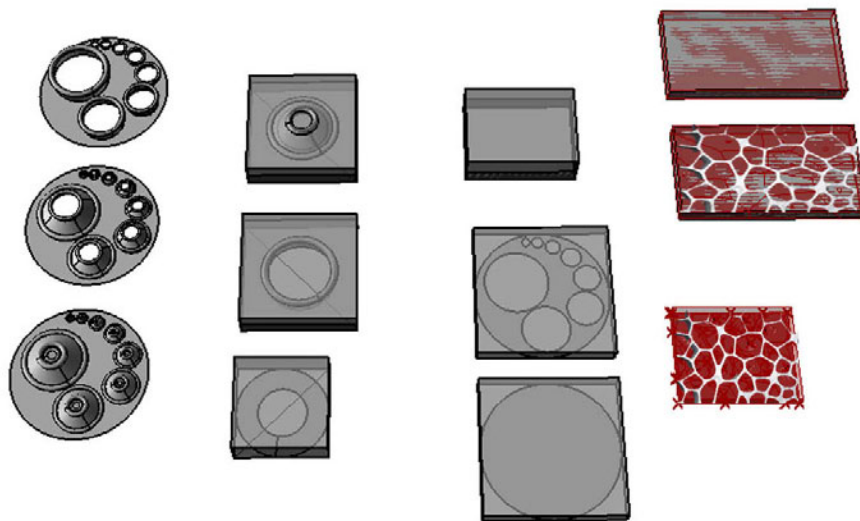


Figure 67: Initial models of various modular configurations (Circle, Rectangle, Organic)

SURFACE SKINS

Following this, some quick investigations were performed to determine which surfaces would best apply to the design goals. Two surfaces were chosen to begin with:

- 1) **RECTANGLE Module:** A basic rectangular grid to initialize my dynamic surface, responsive to the SUN PATH / Light (Fig.68).

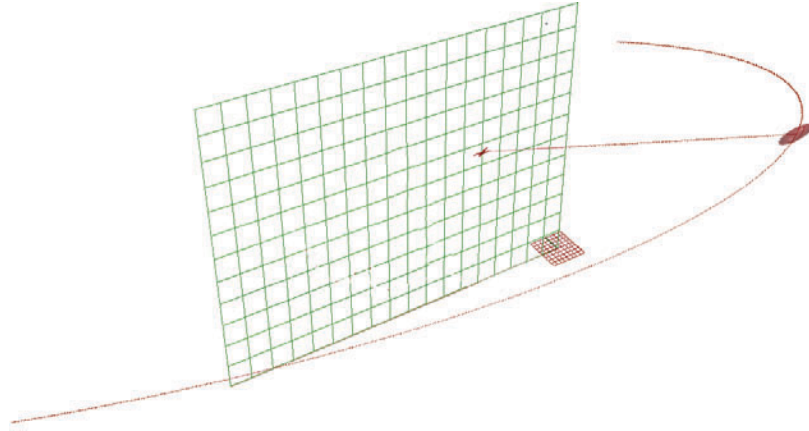


Figure 68: Initial modeling for LIGHT dynamic (Rectangular Design Module)

- 2) ORGANIC: A static, curvilinear surface for the responses generated to the WIND PATTERN / Air (Fig.69).

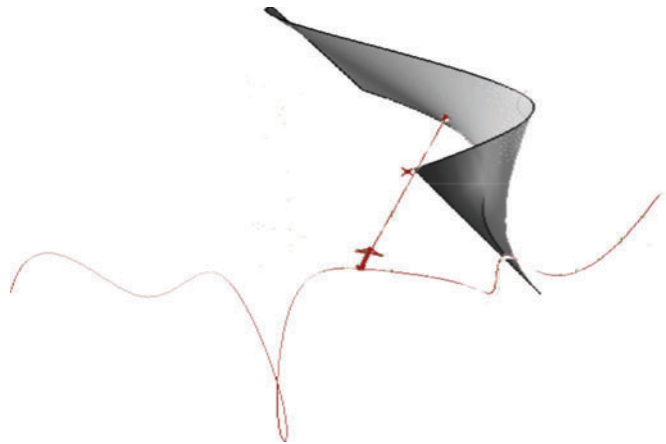


Figure 69: Initial modeling for WIND dynamic (Organic Design Module)

SCRIPTING DYNAMICS

1) RECTANGLE Module

- a. Attractor (SUN paths) and surface morphing: Using the point cloud from the script, I applied an attractor point to the rectangular grid, and transformed it into a new dynamic freeform surface that responds to solar movement and direction (angle, azimuth). (Fig.70)

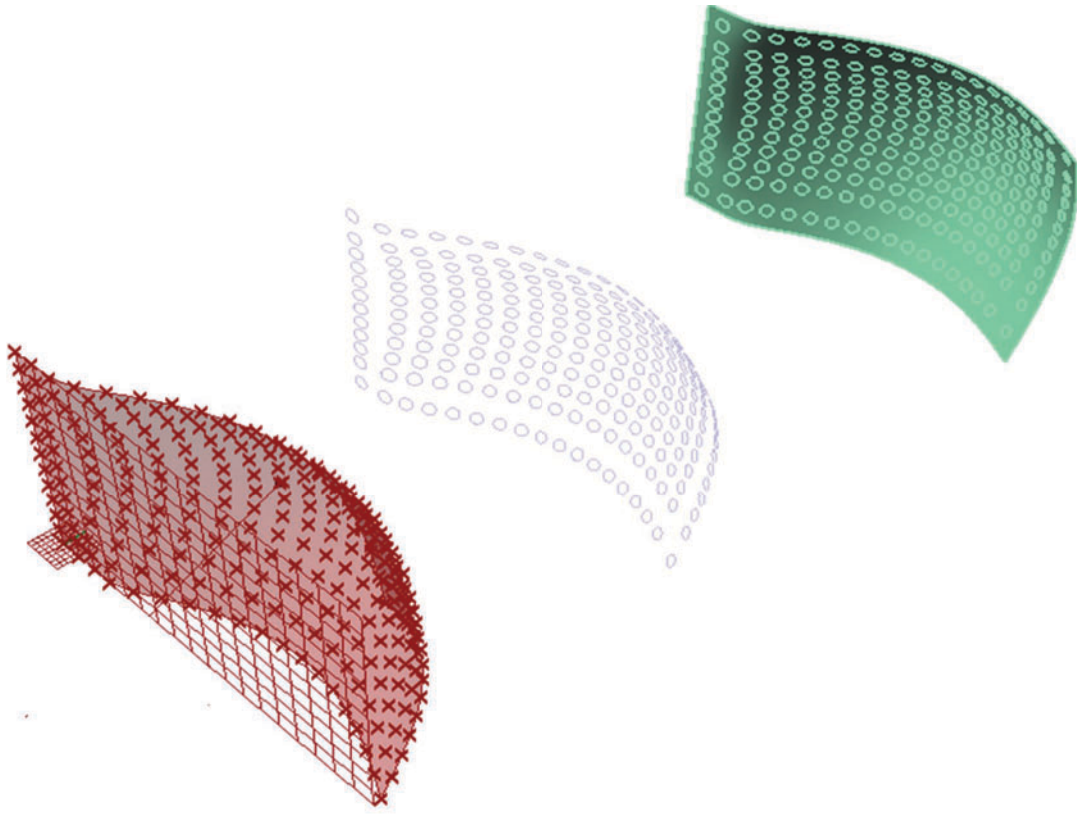


Figure 70: Surface alteration for LIGHT dynamic (Rectangular Design Module)

- b. Basic rectangular blinders as modules were applied, using scripting, (Fig.71) to the dynamic skin surface. As the sun changes position with respect to the responsive blinders (Figs.72, 73, 74):
 - i. The entire surface morphs and shifts away from the sun's position, i.e., source point (Seasonal)
 - ii. The blinders adjust in angle and rotate to keep the direct sunlight away from the interiors of the building. (Diurnal)

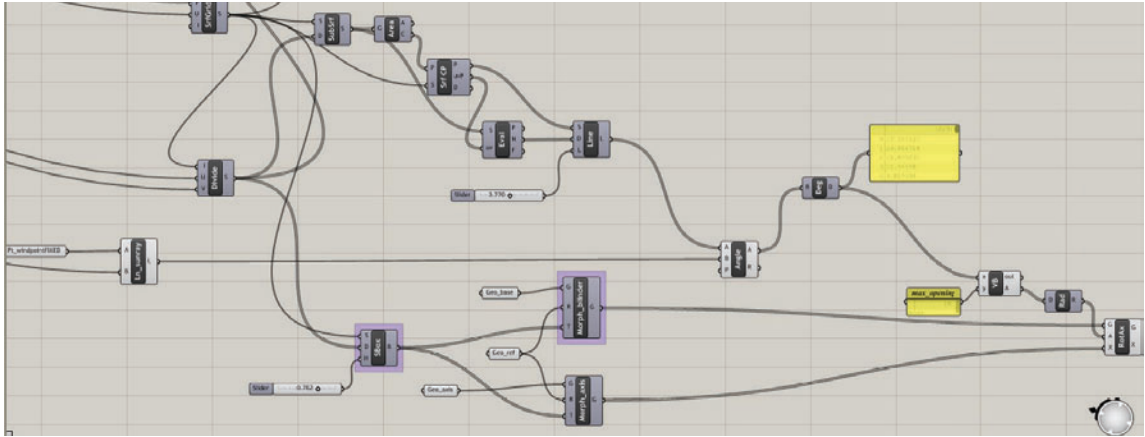


Figure 71: Scripting RECTANGLE module & adaptation to SUN movement

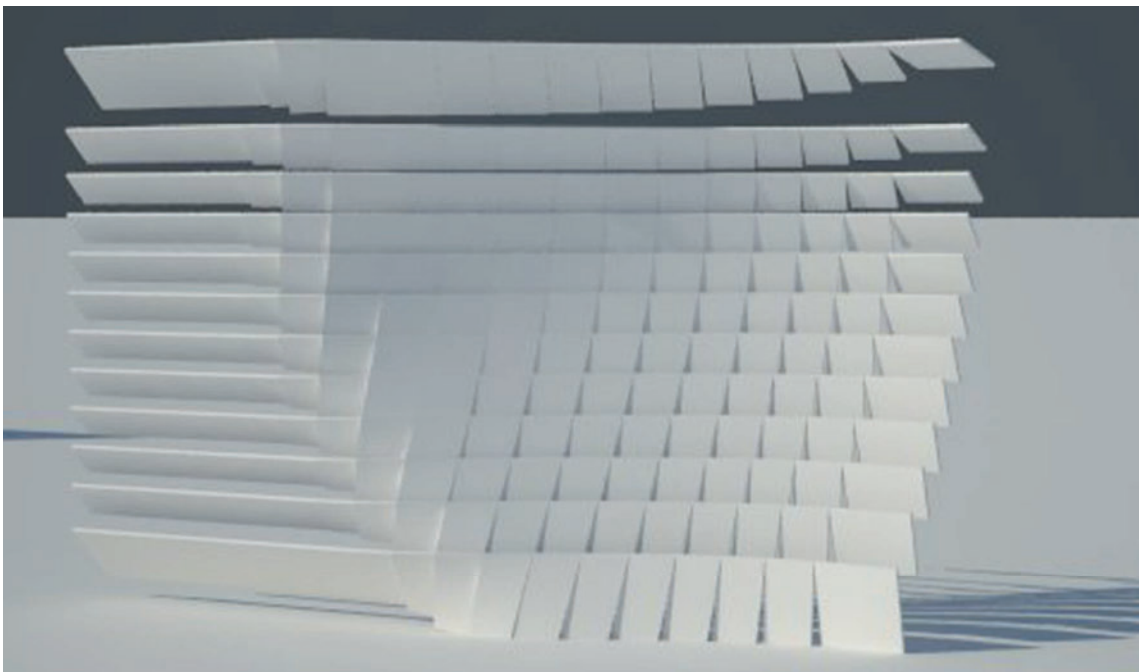


Figure 72: RECTANGLE design module (Equinox, Morning)

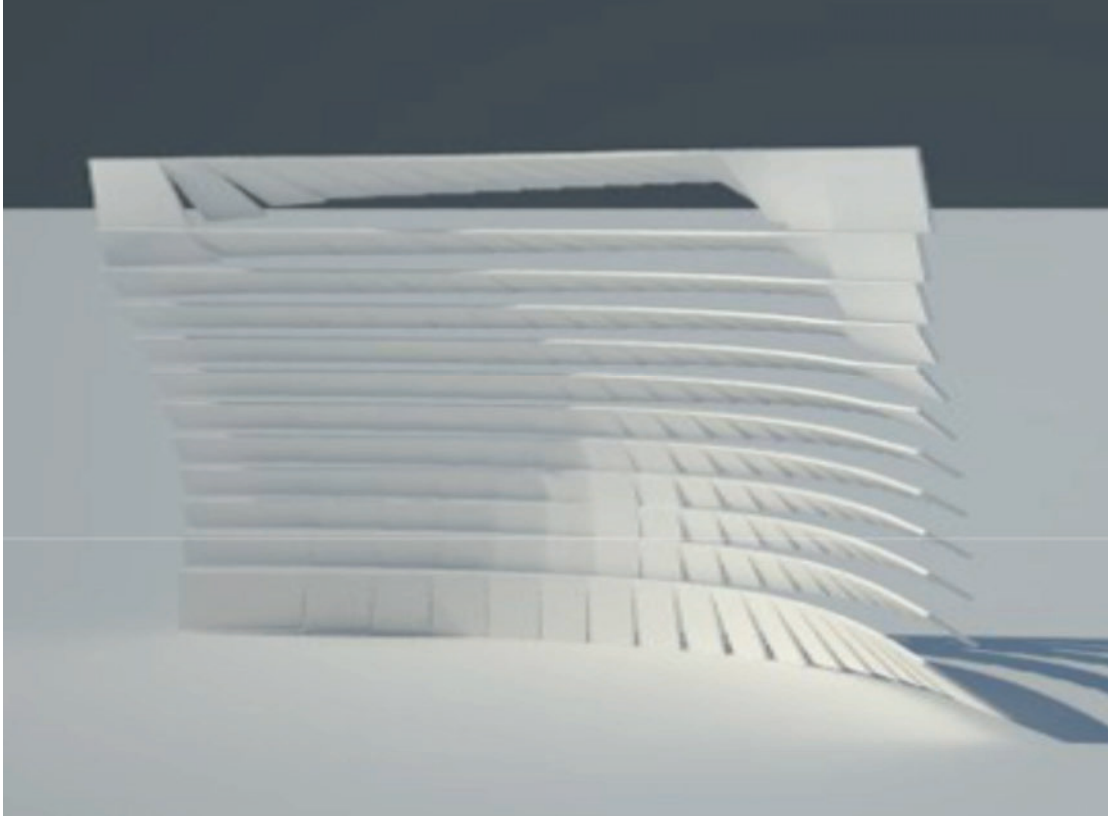


Figure 73: RECTANGLE design module (Equinox, Noon)

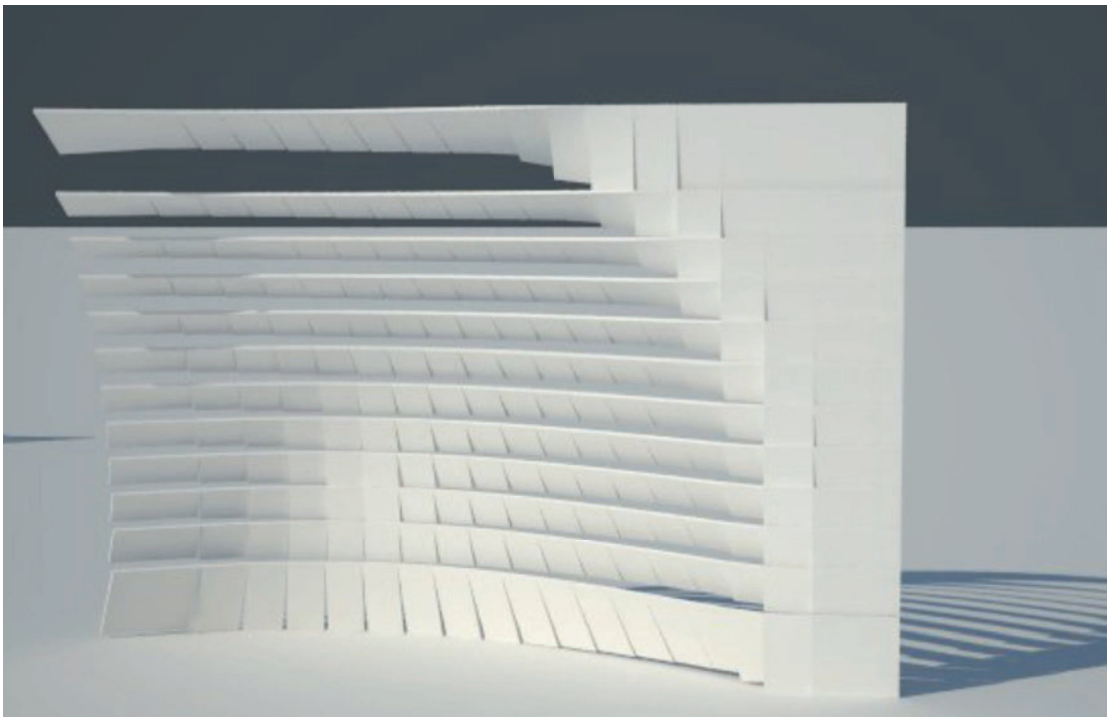


Figure 74: RECTANGLE design module (Equinox, Evening)

2) ORGANIC Module

- a. First, a modular panel with organic, naturalistic opening sizes and shapes was created (Fig.75)
- b. The wind pattern and paths were added to the script, to enable the modules to “follow” adaptively; this was applied to the organic surface module, which in turn was applied to the building skin (Fig.76)

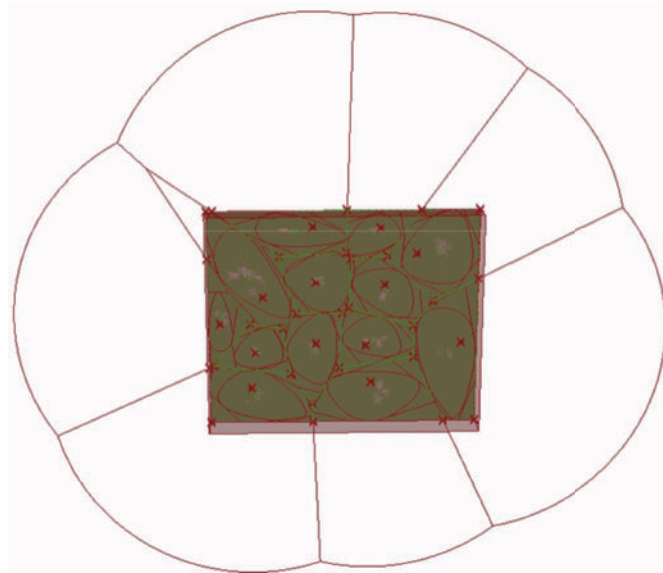


Figure 75: Organic module for WIND dynamic (POROSITY)

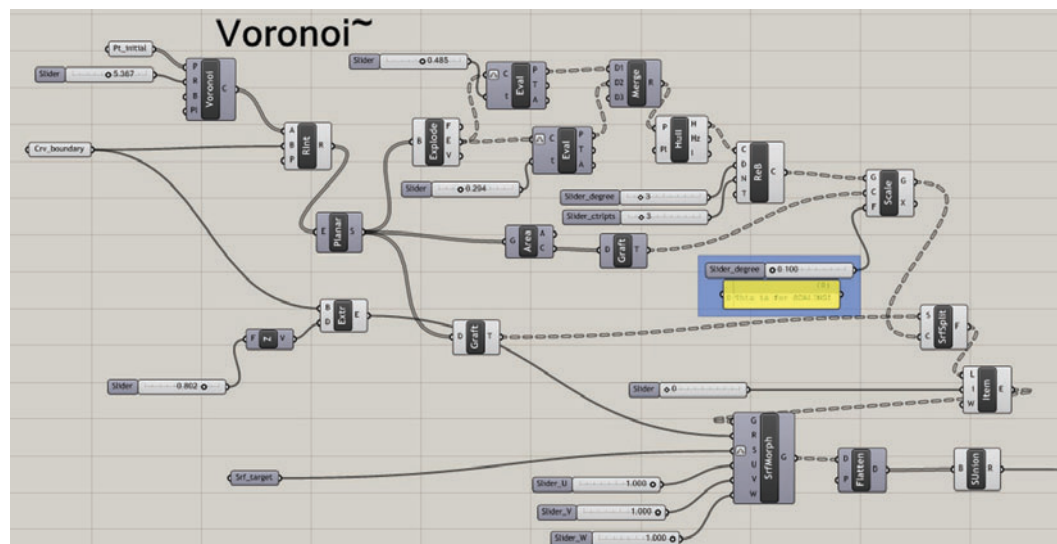


Figure 76: Scripting ORGANIC module & adaptation to WIND pattern

The organic modules were applied and adjusted (ratio of opening size to panel size), such that the ratio was achievable from completely closed to keeping open at seventy five percent (75%).
(Figs.77, 78)

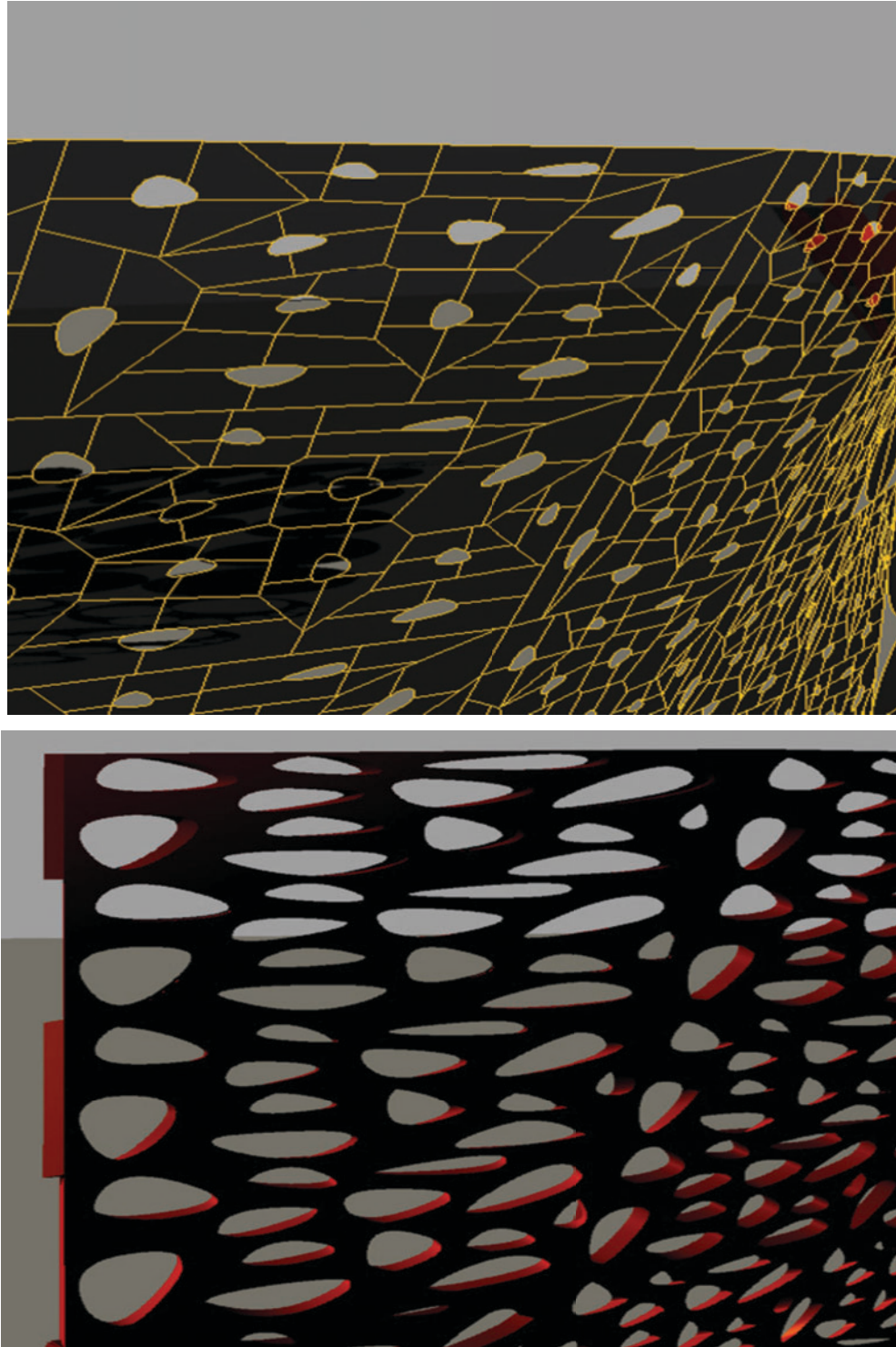


Figure 77: Porosity adaptation for WIND dynamic (Organic Design Module)

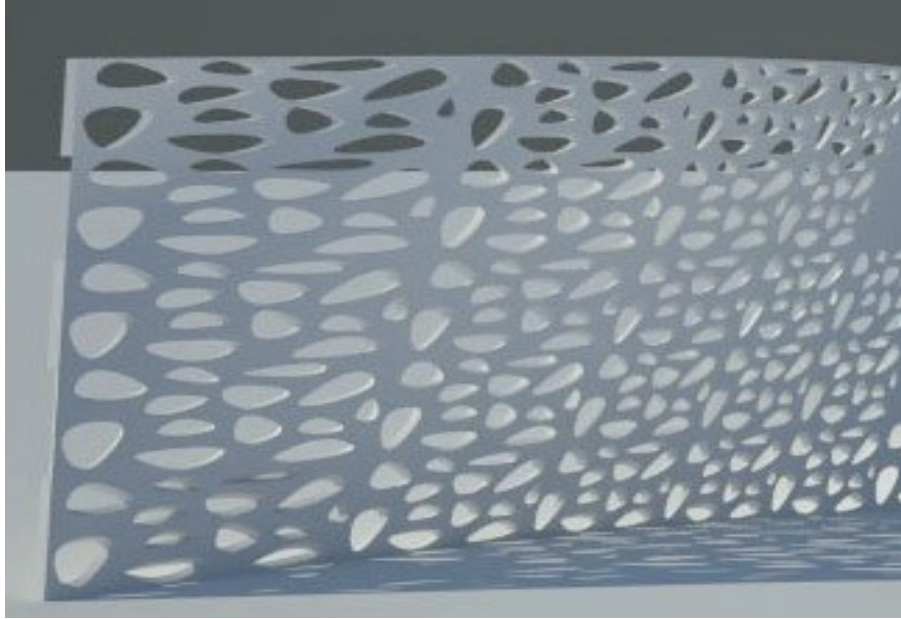


Figure 78: ORGANIC design module (High wind speed = Low surface porosity)

As the point on the wind pattern (airflow) curve advances closer to the building envelope, the surface porosity of the design modules decreases adaptively. (Fig.79)

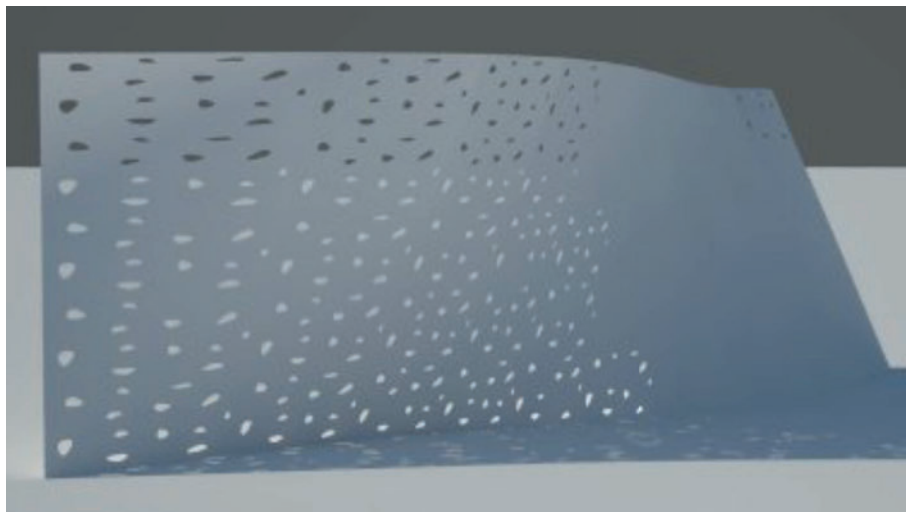


Figure 79: ORGANIC design module (Low wind speed = High surface porosity)

3) HYBRID Module

- a. A combination of scripts was “pathed” to apply to the original dynamic building skin; thus, a “hybrid module design” was conceptualized and simulated in the analyses (Figs. 80, 81, 82)
- b. The solar path was given greater priority over the wind pattern, should the points on the sun path and wind curve collide (Fig.80).

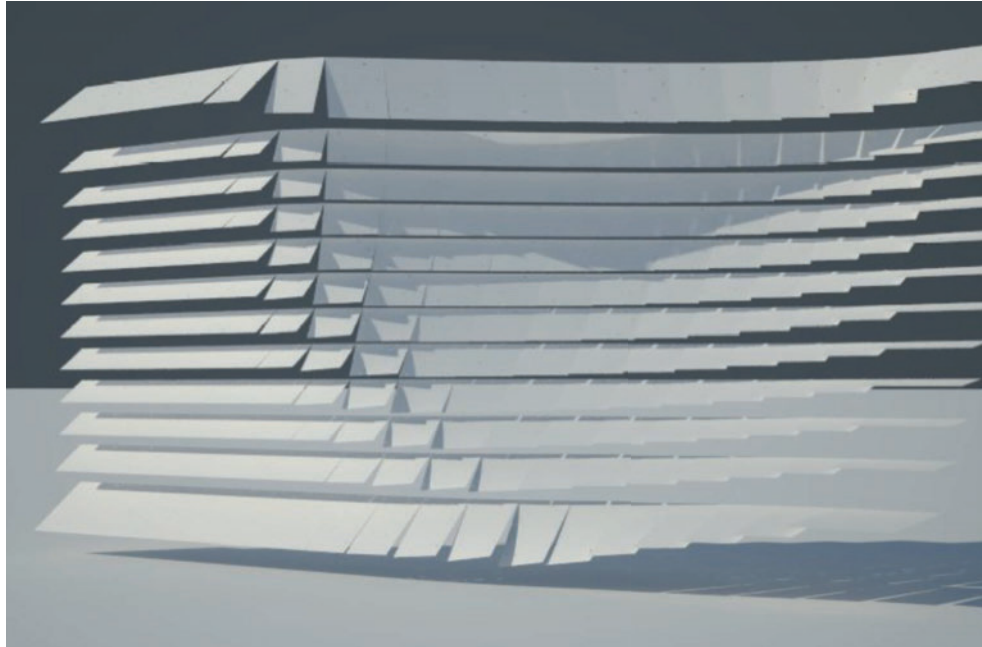


Figure 80: HYBRID design module (Winter solstice, Morning, Low surface porosity)

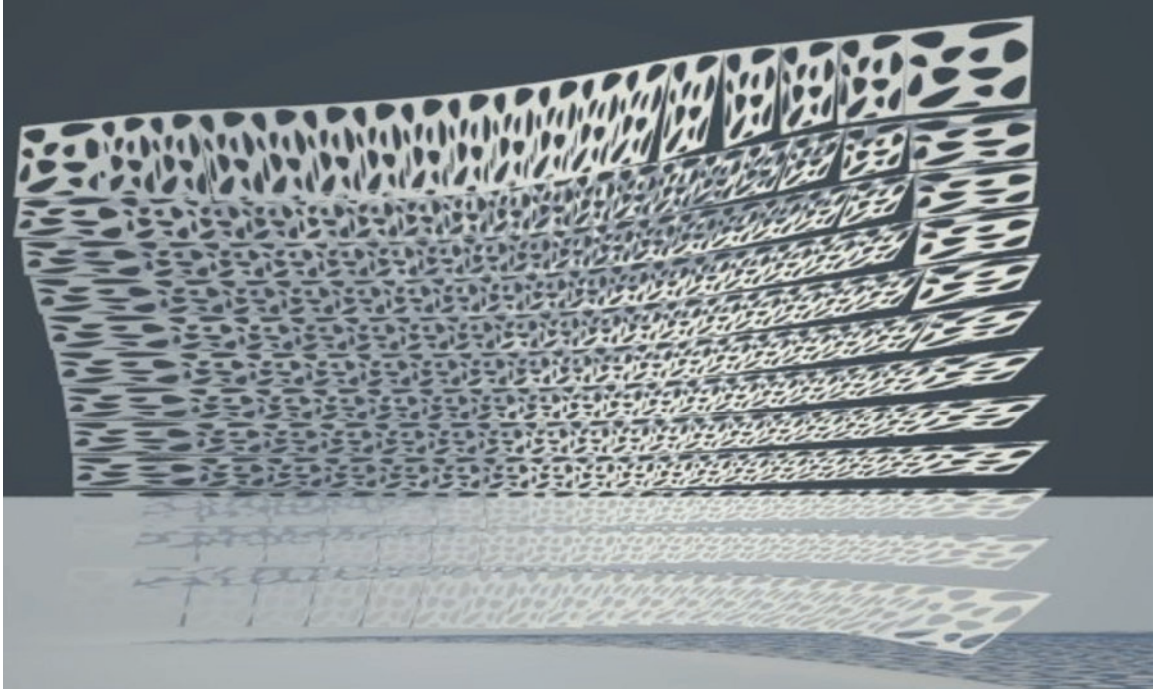


Figure 81: HYBRID design module (Winter solstice, Noon, High surface porosity)

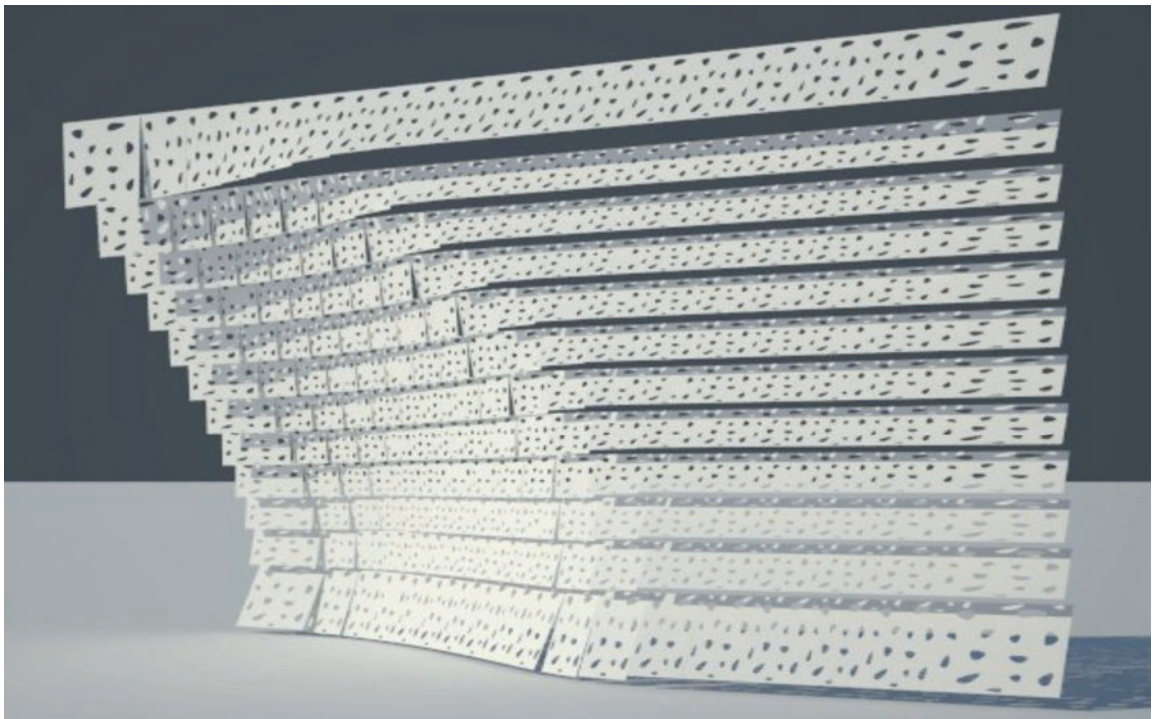


Figure 82: HYBRID design module (Winter solstice, Evening, Medium surface porosity)

4.2 BIOMIMICRY (Materials): Analysis and Discussion

Tables below (Tables 2,3,4) provide summarized descriptions of the biomimetic and nanotechnological materials and systems that were explored in each category: LIGHT, WIND, HEAT. The highlighted areas indicate where use of these nanomaterials and technologies, in application to the design modules: A (Rectangular), B (Organic), and AB (Hybrid) will improve material changes within the envelope, and thereby will positively effect lighting, airflow, and thermal conditions.

Summary diagrams (Figs.83-86) each show the translation from biomimetic processes and functional characteristics analyzed, to the nano applications of the design modules created, as they would apply to the building façade (dynamics of surface skin).

Rainscreen cladding/Double skin facade systems: Wood, metal, glass	Passive system: "guard sheet" & "inner sheet". Metal, porous ultrathin-Si, plastic/gel
Sailcloth fins and other flexible shading devices; inclusion of mechanical movement/energy	Artificial super skins: silicone embedded with single-walled CNTs Microbelts: PVDF (polyvinylidene fluoride) Airflow sensors: Polymer SU8 connected to a flexibly suspended sensor plate

Table 2: Traditional vs. Nano materials (Daylighting Strategy)

Solar cells (fixed, non-tracking), silicon-based, thin-film cell arrays	Tracking solar cell materials (Aluminum, Steel)
Metallic (mechanical): steel, aluminum, etc. Current commercially available light driven actuating materials such as polyvinylidene fluoride (PVDF) that are thermoplastics	Graphene (single-layer Carbon atoms) combined with PDMS (polydimethylsiloxane) or dimethicone

Table 3: Traditional vs. Nano materials (Natural Ventilation Strategy)

[illegible]

Table 4: ‘Bio-to-Nano’ Materials and Technology Matrix

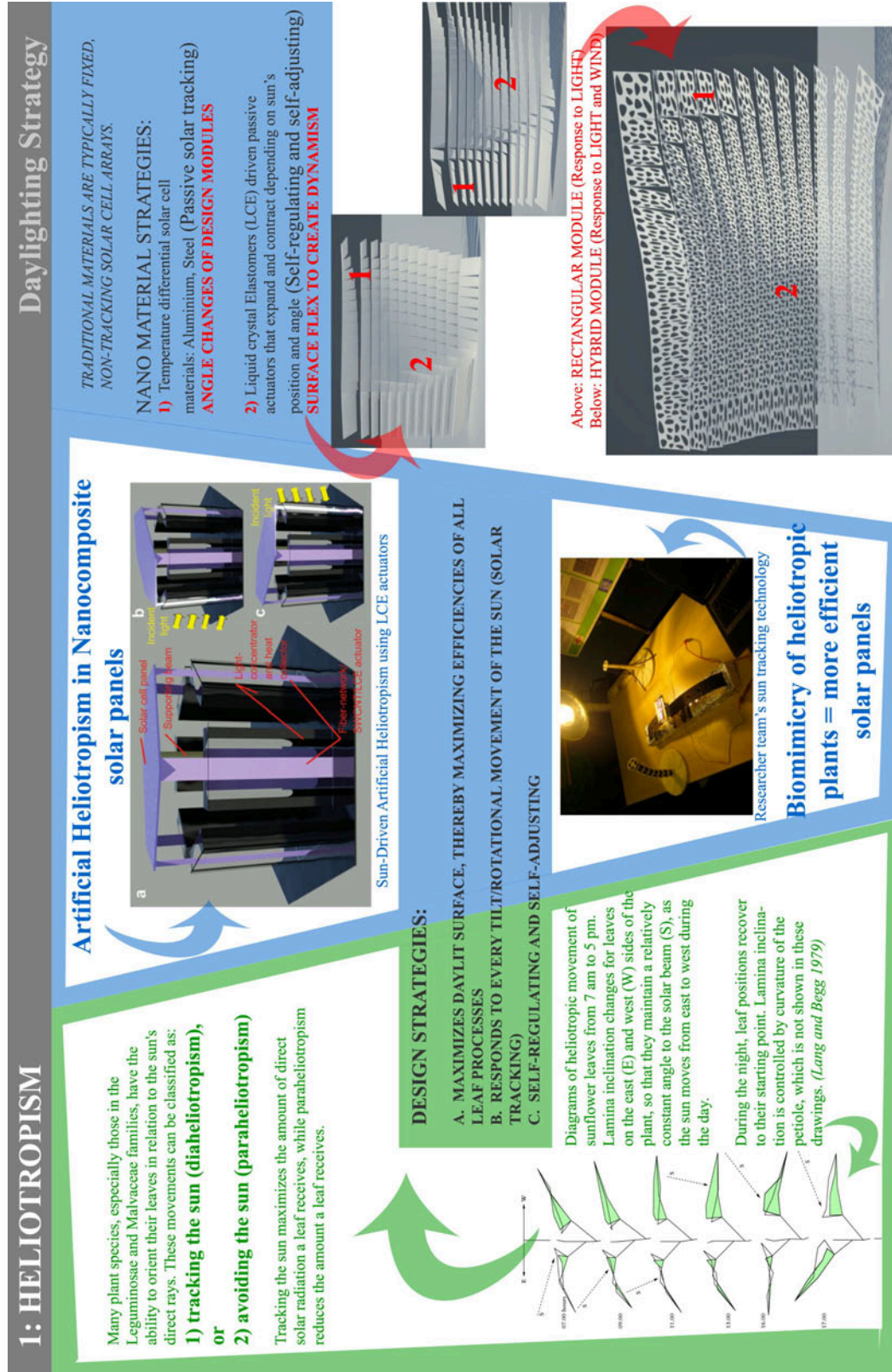


Figure 83: Summary infographic: HELIOTROPISM (Daylighting)

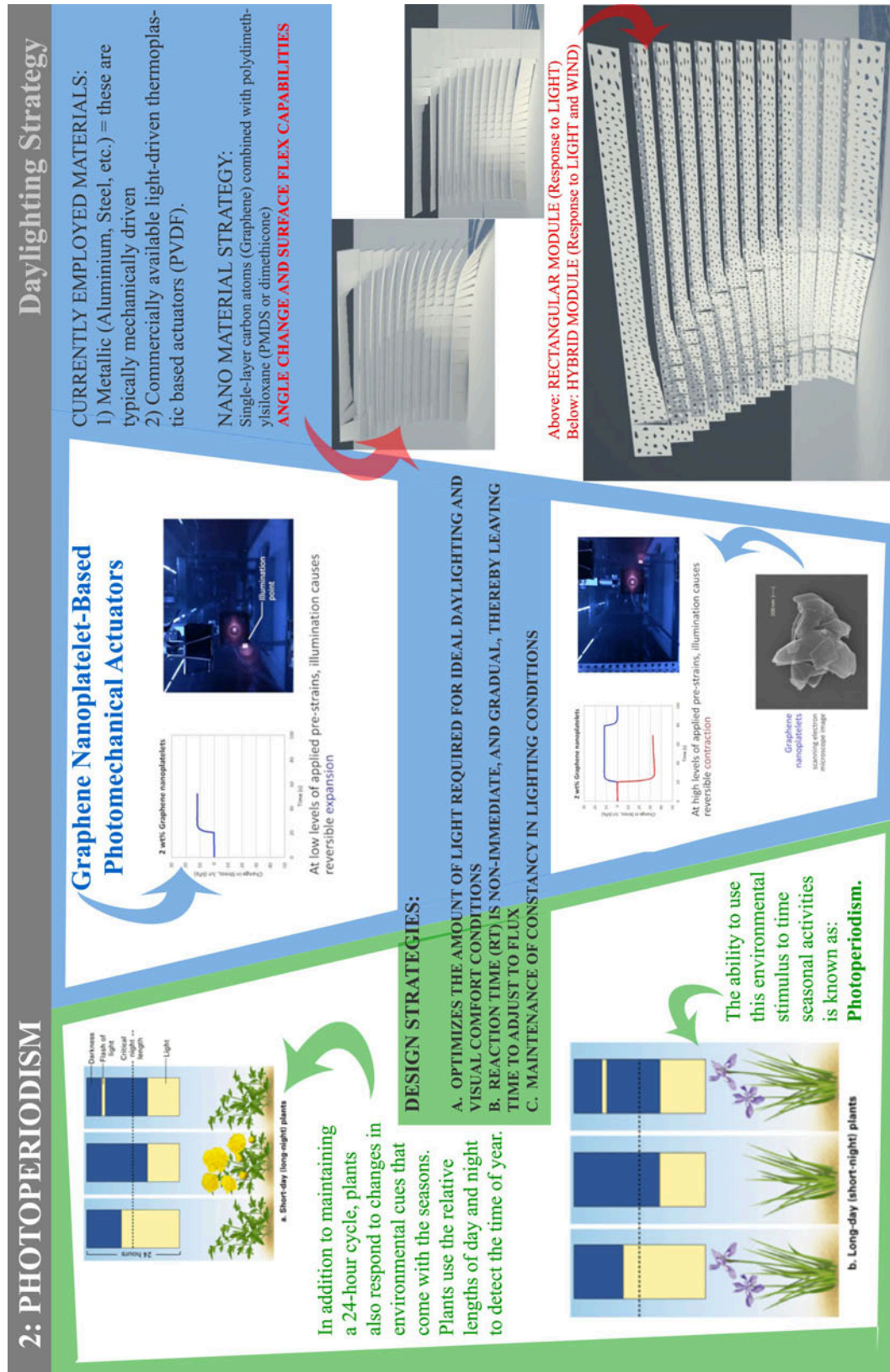


Figure 84: Summary infographic: PHOTOPERIODISM (Daylighting)

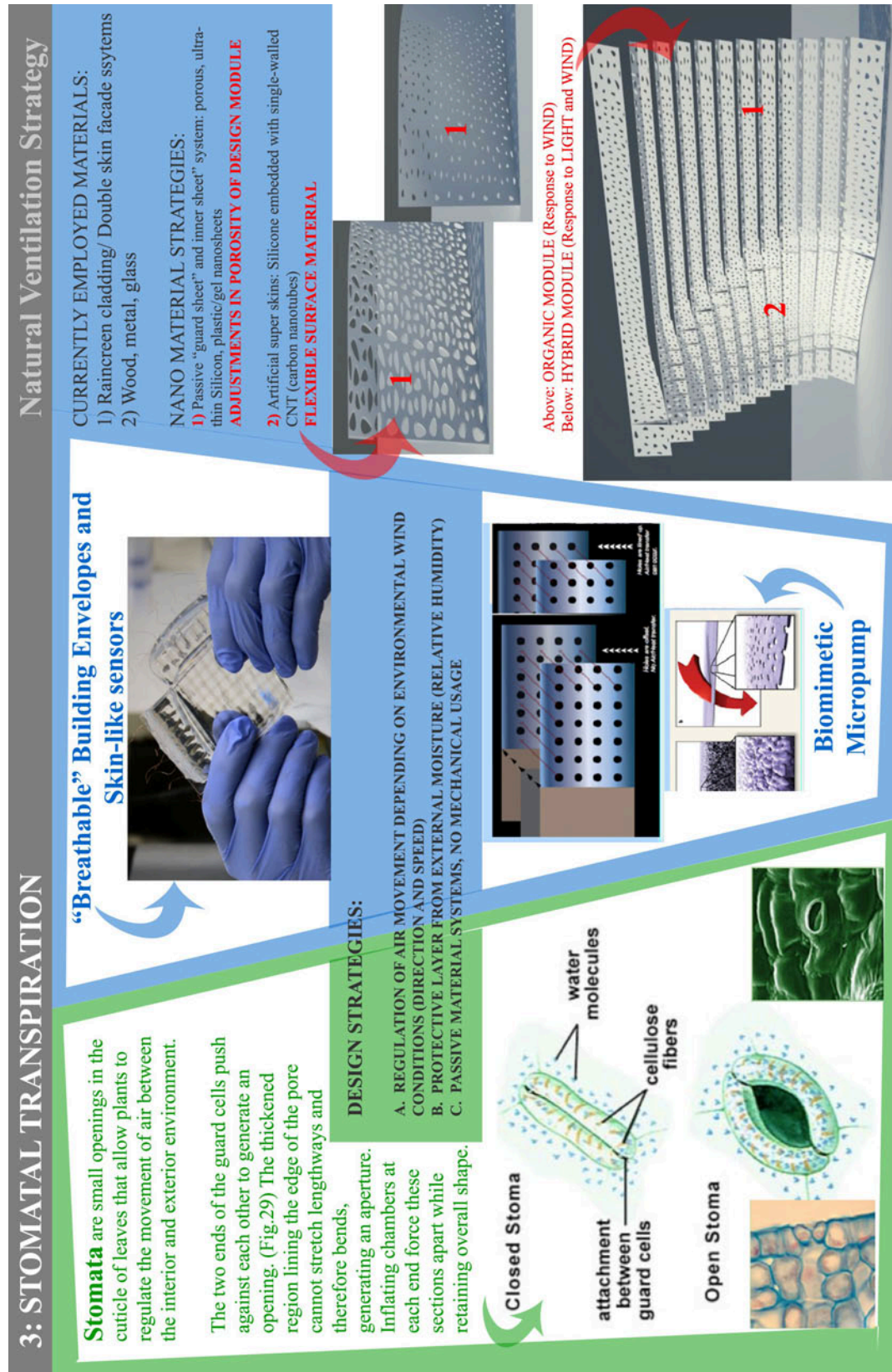


Figure 85: Summary infographic: STOMATAL TRANSPIRATION (Natural Ventilation)

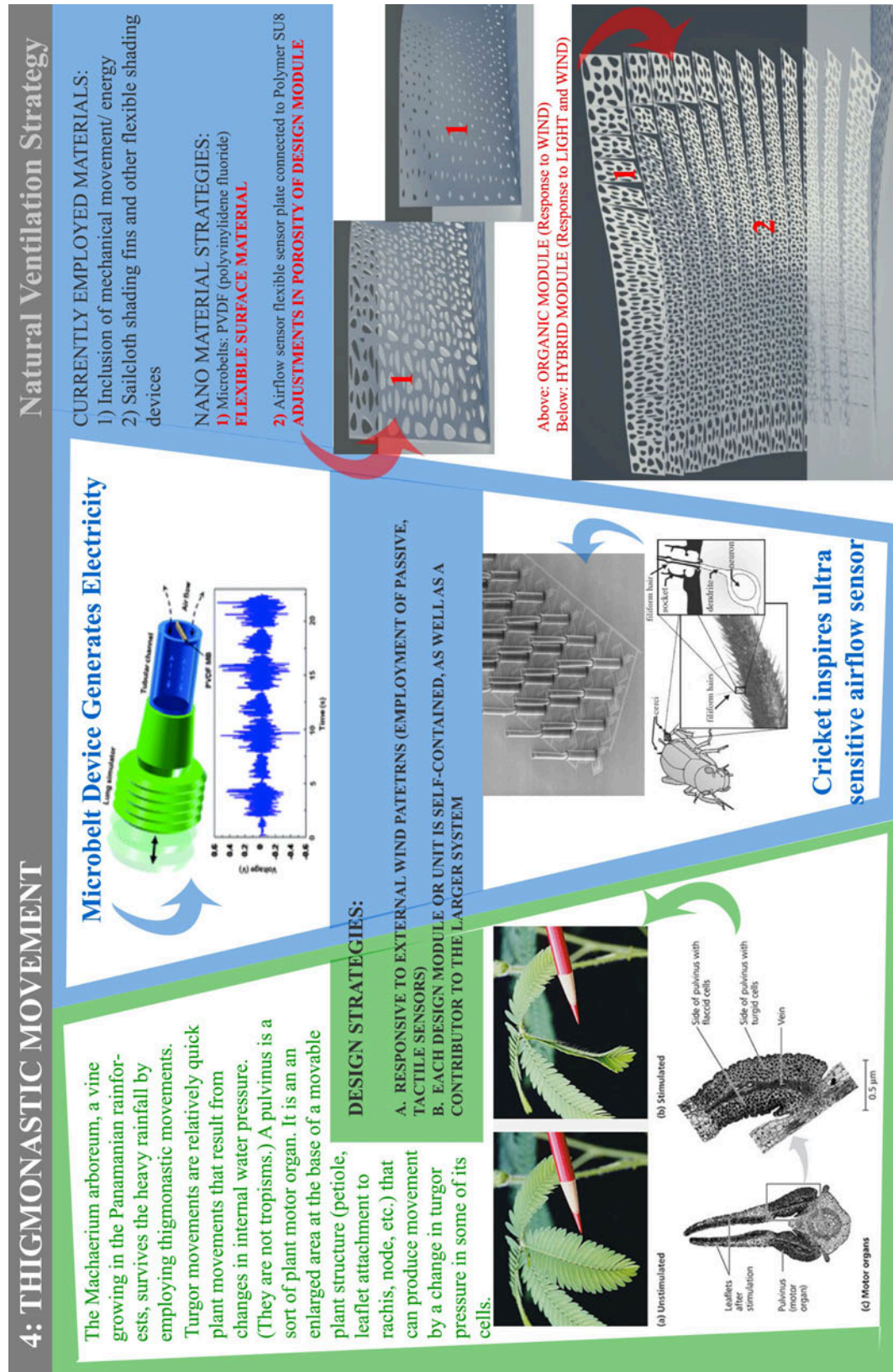


Figure 86: Summary infographic: THIGMONASTIC MOVEMENT (Natural Ventilation)

4.3 BIOMIMICRY (Performance): Analysis and Discussion

The following pages will provide a detailed overview through the analysis and results (simulations run through Revit, Autocad, Sketchup and Ecotect software) to determine daylighting levels, airflow rates and pressure, and a series of thermal analysis.

[O] Design Module (BASE)

General notes, as observed of the site conditions:

1. The amount of light (as observed within the FCA office environment over the past several months) indicated that minimal glare is observed; there are sufficient lighting levels, save for the occasional need for task lighting.
2. Aesthetically, the daylighting patterns from the brise soleil are quite architecturally interesting as well as non-invasive, visually/aesthetically. The view corridors are kept intact and although the shading devices might lend a “blocky, heavier” feel to the exterior elevations due to their sheer mass, the interiors are lighter and airier, and the spaces are well shaded throughout the year.
3. HVAC settings maintain thermal comfort throughout the year, with no provision currently for passive ventilation methods (no operable window faces).

Daylight analysis (Fig. 87) indicated that the lux levels/values were high along the south façade, and even with an open plan rendering and simulation, the natural light was more than sufficient for naturally lighting the interiors, including even a few centrally located zones:

1. High daylighting levels (≥ 800 lux) or 80 foot-candles. This indicates insufficient shading options on the south façade.
2. Maximum natural lighting levels on the south, and southeast façade edges
3. The brise soleil is possibly a source of “overshading” on the north façade. Although the daylighting levels here are normal (200-300 lux), there is an absence of uniform daylighting/shading levels.

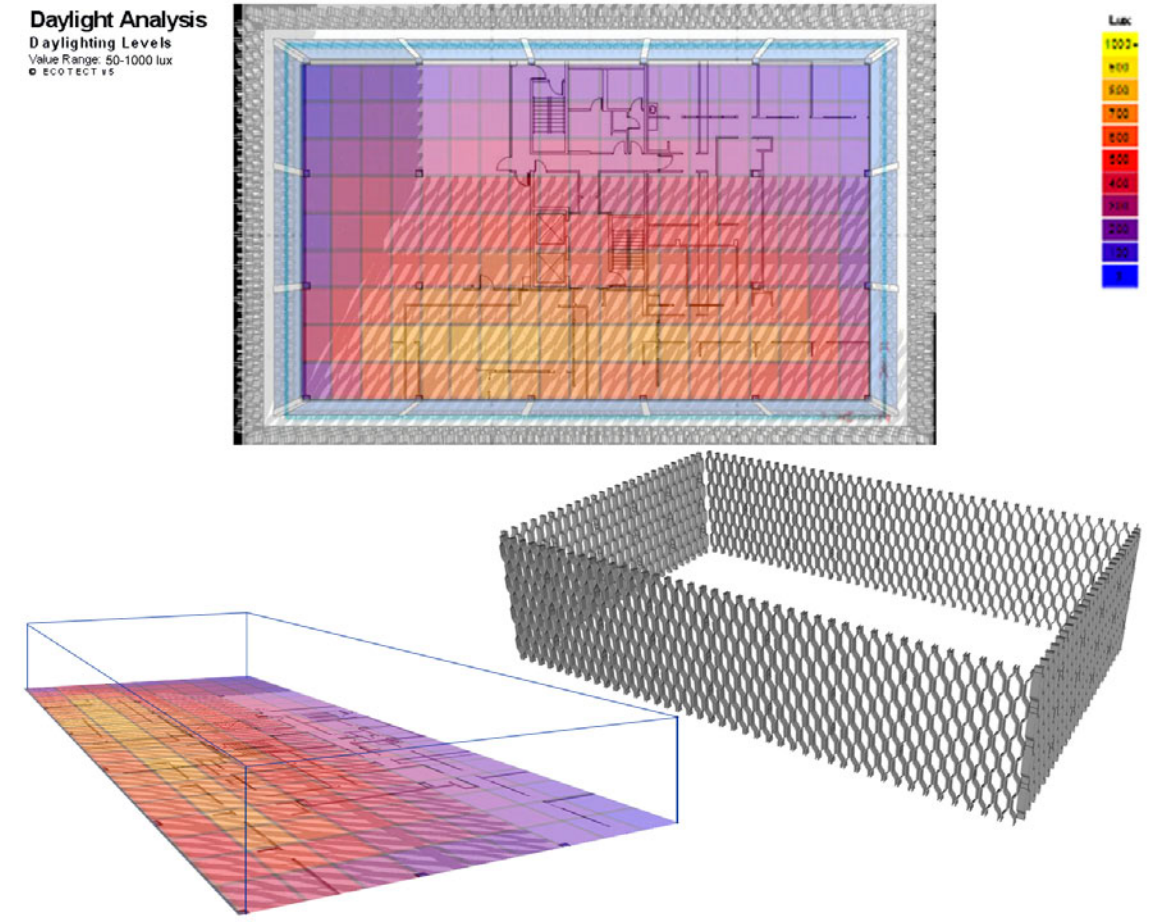


Figure 87: Daylighting analysis: [O] Base Model

Thermal analysis for option “O” (Base module) revealed that the space required minimal air velocity to create a comfortable working environment. However, the materials used indicated that the passive heat gains occurred primarily as a result of solar heat gain through the single glazed facades, and that heat losses occurred due to conduction (this reflected on the use of the building materials). Temperatures were close to the exterior environmental temperatures, with increased fluctuations occurring through the middle part of the day (analysis run on an average hot day of the year (October 5), through a 24-hour period. (Fig. 88).

1. Mean Radiant Temperatures (MRT) within the floor space went slightly above the comfort band values (displayed 28°C to 32°C, with 34°C temperature at 2pm). This also demonstrated a change from the comfort zone, responding to a corresponding drop in wind speed values.
2. More than 80% of the heat gains within the space occur as a result of the solar heat

radiation (yellow) on the wall surfaces (peak value of over 104kWh/m^2) occurring on the average hottest day (October 5), recorded at the site.

3. Conduction (red) accounted for the second-highest heat gains, followed by ventilation gains (green). These gains occur as a direct result of the instantaneous temperature differences between the interior and exterior environment, as well as being dependent on the “U-value” of the building element. Conduction gains can be reduced significantly with material changes and adjustments.
4. Ventilation gains occur as a result of infiltration (or air movement through the façade), and this is possibly caused due to an absence of thermal breaks within the surface of the façade.

Design Modules A, B, and AB will look into reduction of these passive heat gains and eliminating or minimizing their sources, with proper design and analysis.

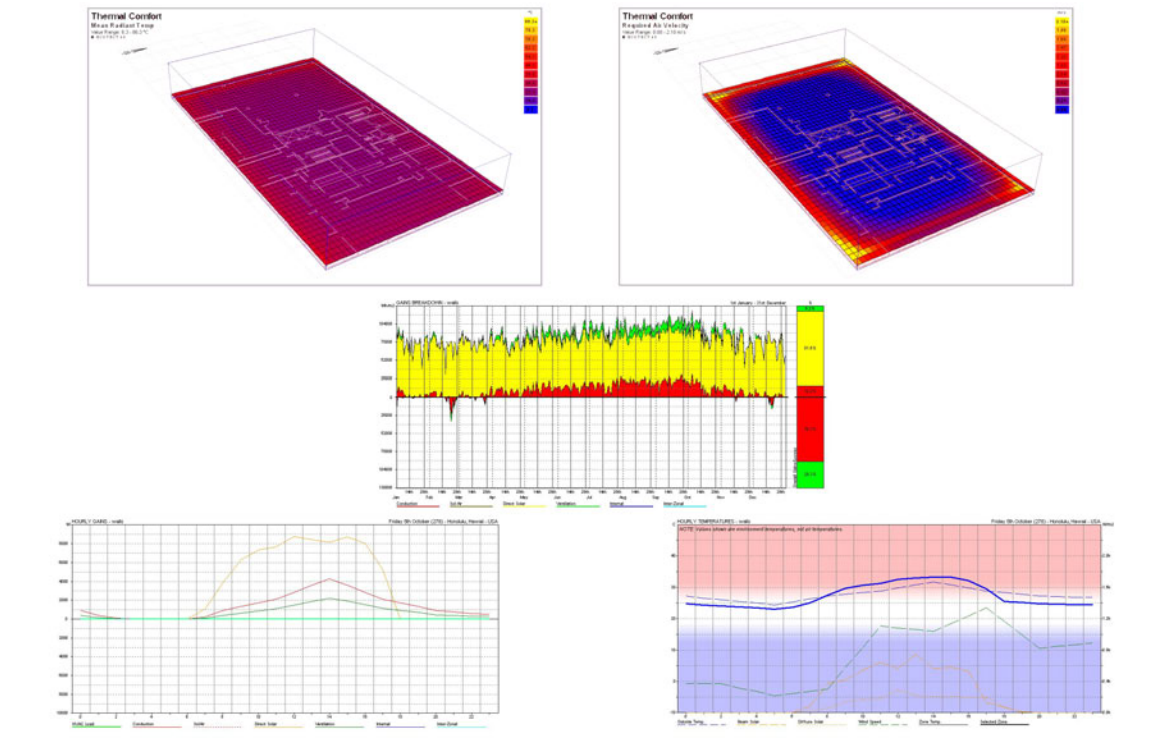


Figure 88: Thermal analysis: [O] Base Model

Daylighting Analysis: SUN PATH DIAGRAMS

Sunpath diagrams constitute a convenient way for designers to ascertain solar access and shading requirements for a given location and for a specific time of the year.

A range of Sunpath Diagrams are shown here for Honolulu's location. (Figs.89-91) They all provide the same information, but are read in a different way (azimuth and altitude are distributed differently on the chart). The azimuth represents the horizontal angle that the projection of the Sun's position makes with North; the altitude illustrates the vertical angle that the Sun makes with the horizon.

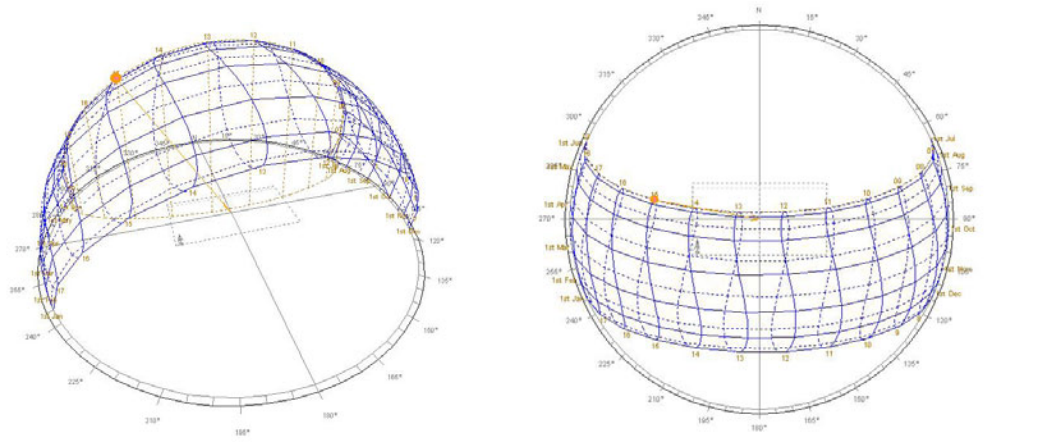


Figure 89: Sun path diagram: June 21 (SUMMER SOLSTICE)

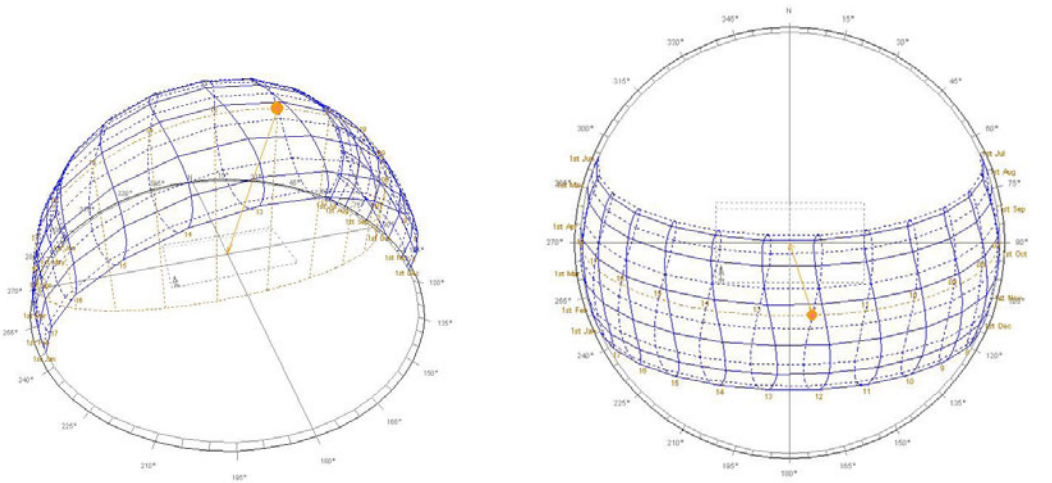


Figure 90: Sun path diagram: March 21/ September 21 (SPRING/ AUTUMN EQUINOX)

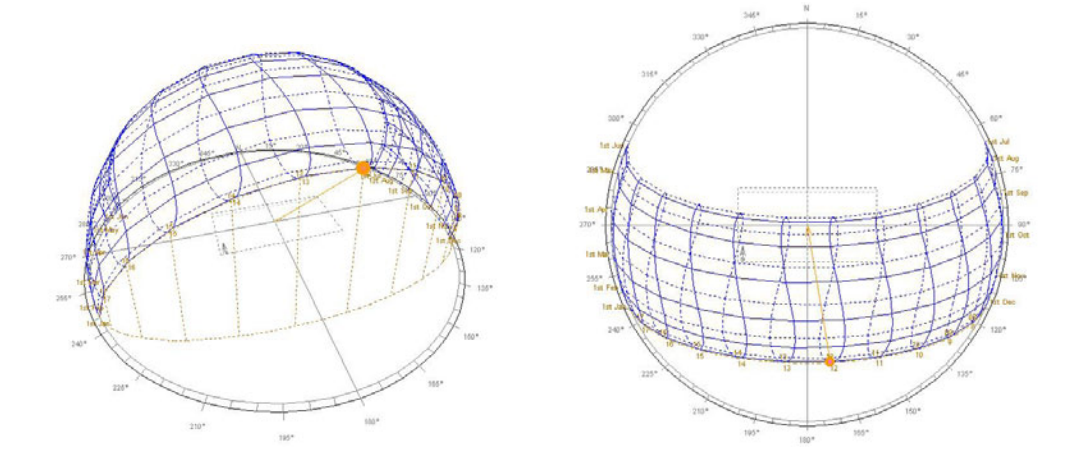


Figure 91: Sun path diagram: December 21 (WINTER SOLSTICE)

Natural Ventilation Analysis: WIND ROSE DIAGRAMS

A wind rose can be used to characterize the direction, speed, and frequency of wind. It gives detailed information about wind direction and frequency for a month or a whole year. The wind rose is divided into sixteen pie-shaped sectors in which the frequency (hours) of wind is shown for summer and winter (Figs.92,93). The concentric circles indicate the wind speed (km/h). The degrees around the outer circle provide the azimuth of the wind, or the direction from which the wind blows. The semiannual wind rose for Honolulu, Hawai'i indicates that the wind comes predominantly from the north-east with greatest frequencies in the 20 to 30 kmph range. The wind rose during the winter months reveal that south-west winds also occur regularly. Trade winds typically moving at 15 to 20 mph from the north-east to the south-west; these winds are steady throughout much of the year and tend to be stronger in the afternoon rather than at night. Southerly winds occur with regularly during the winter months as winter storms can bring in heavy winds and rains.

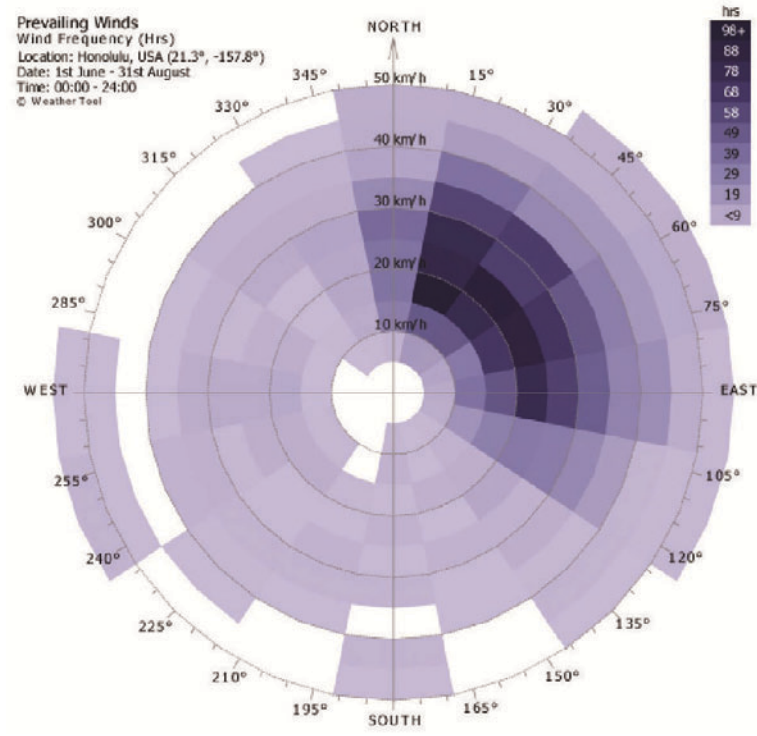


Figure 92: Summer Wind Rose: Winds from Northeast (20-30 kmph)

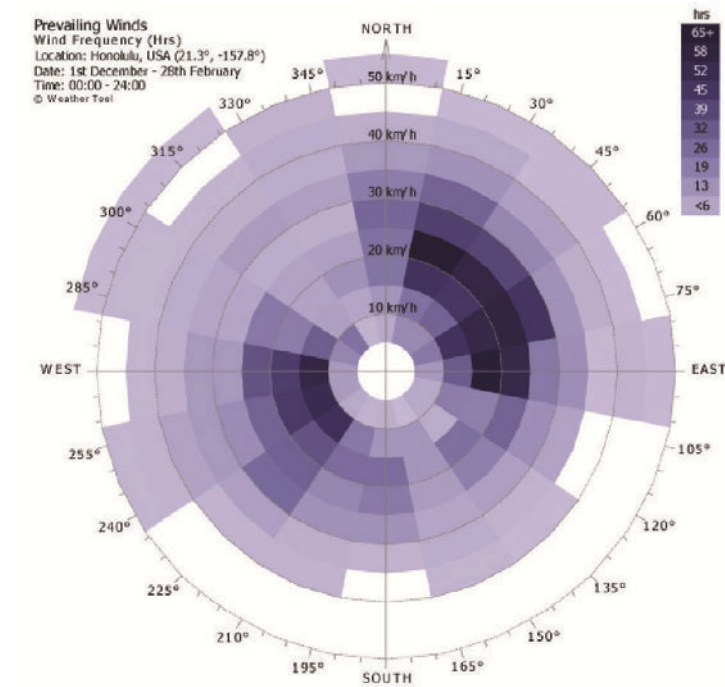


Figure 93: Winter Wind Rose: Northeast (20-30 kmph) and Southwest (15-20 kmph)

[A] Design Module (RECTANGULAR)

Daylighting Analysis

Summer solstice, June 21: This is when the sun is at its northernmost position in the sky along the sun path diagram. At noon, it is at the highest altitude angle (91 deg vertical from the horizon). As seen from the facade daylighting simulations, the sun rays do not directly penetrate the interior of the building space; however, the daylighting levels appear to be adequate for the office spaces within. (Figs.94-96)

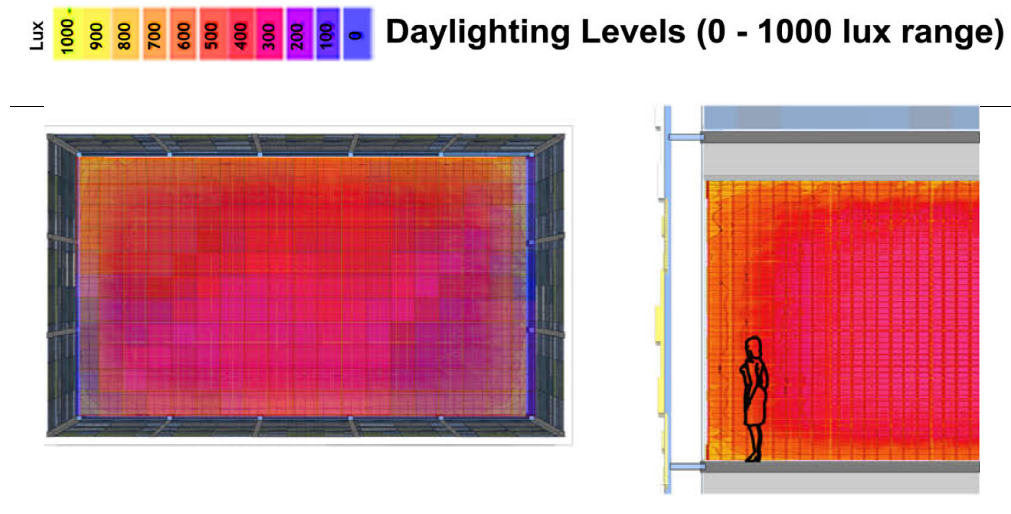


Figure 94: Summer Solstice (June 21); Morning (9:00am)

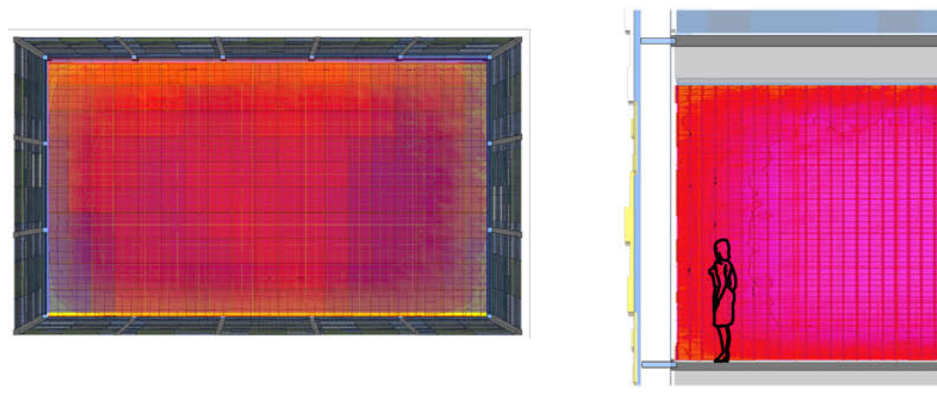


Figure 95: Summer Solstice (June 21); Noon (12:00pm)

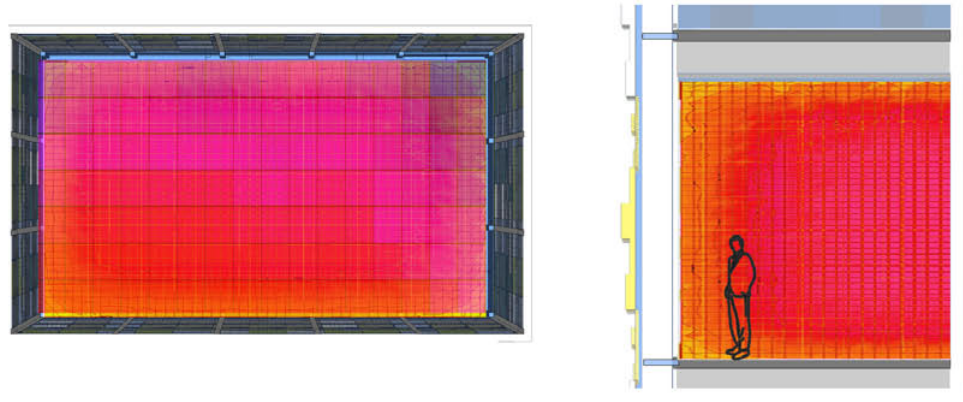


Figure 96: Summer Solstice (June 21); Evening (5:00pm)

Spring and autumn equinoxes (March 21 and September 21): The light reaching the southern facades is the maximum during the afternoon. The solar path is average between the summer and winter paths across the sky. (Figs.97-99)

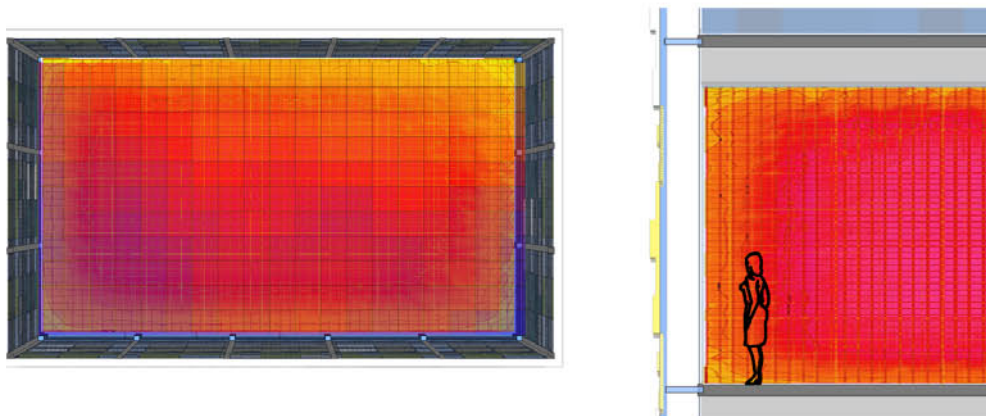


Figure 97: Equinox (March/ September 21); Morning (9:00am)

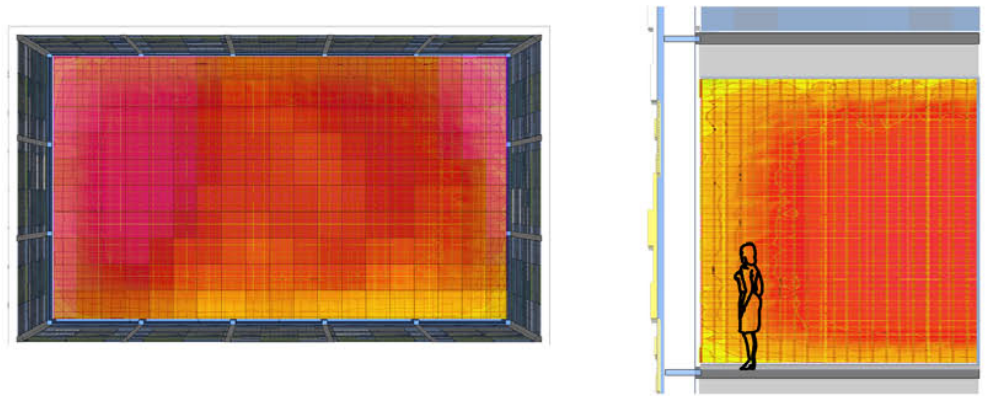


Figure 98: Equinox (March/ September 21); Noon (12:00pm)

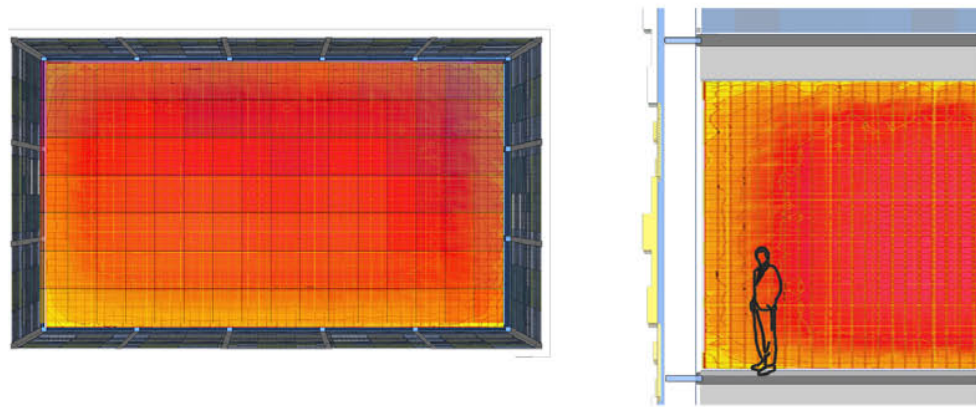


Figure 99: Equinox (March/ September 21); Evening (5:00pm)

Winter solstice, December 21: This is when the sun is at its southernmost position in the sky along the sun path diagram. At noon, it is at the lowest altitude angle (45 deg vertical from the horizon). At these very low angles, there is excess natural lighting levels (as seen in these diagrams), particularly around midday (Figs.100-102).

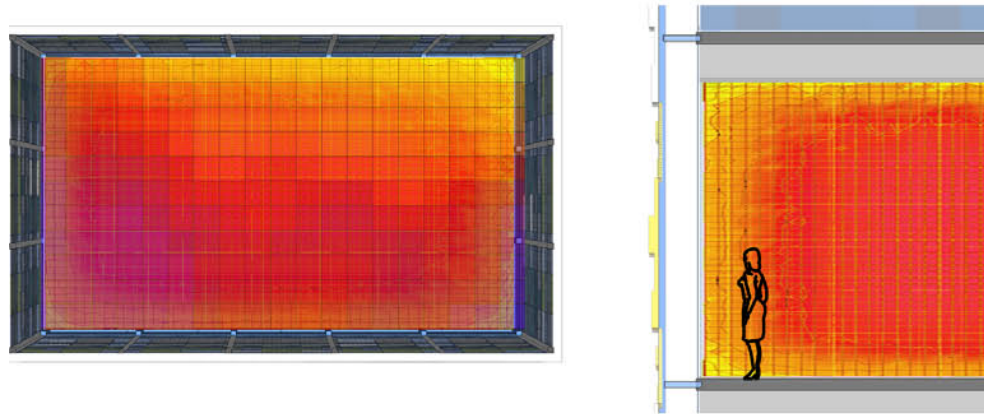


Figure 100: Winter Solstice (December 21); Morning (9:00am)

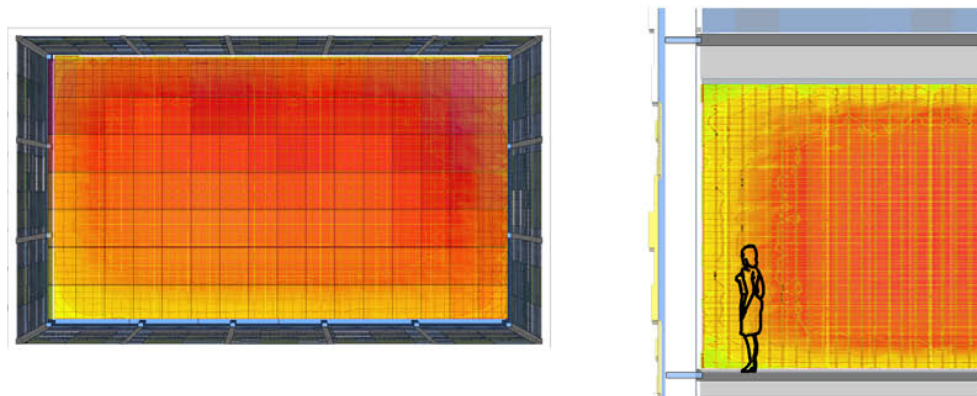


Figure 101: Winter Solstice (December 21); Noon (12:00pm)

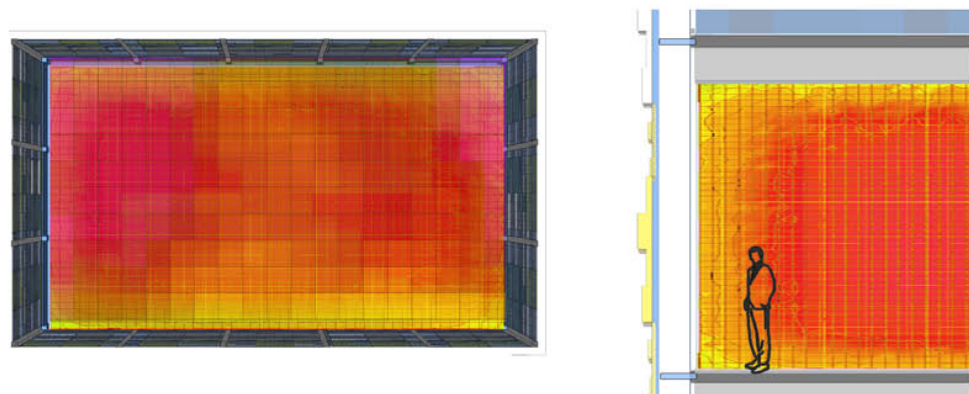


Figure 102: Winter Solstice (December 21); Evening (5:00pm)

CFD Analysis

With the rectangular module (ANGLE) design, the cell pressures are optimum (if not a gradual transition between high and low pressure areas). This can be attributed to the opening size to facade module ratios regulated by the angle of opening. However, the wind velocities are quite ideal within the space during the summer, while the velocities along the facade edges display a slight increase in speeds, thereby accounting for the unevenness in cell pressures (Figs.103,104).

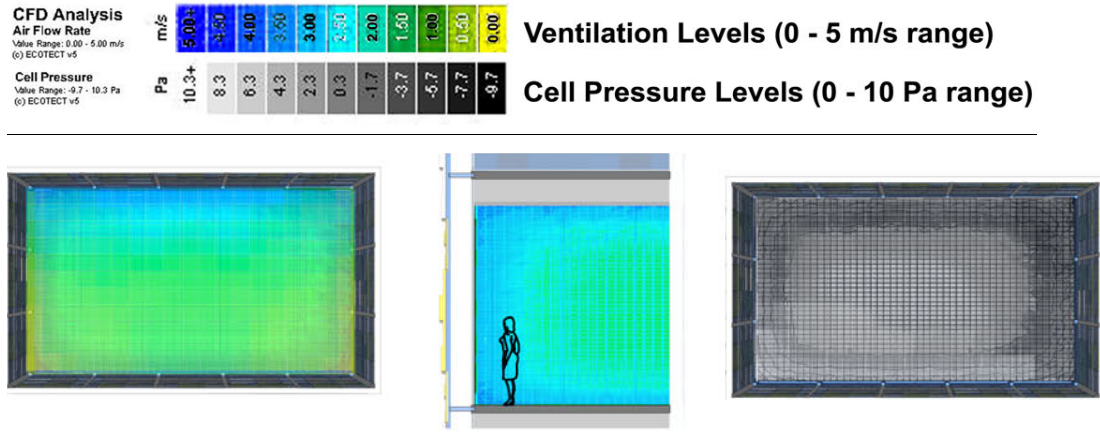


Figure 103: CFD analysis and Cell pressures: Summer months

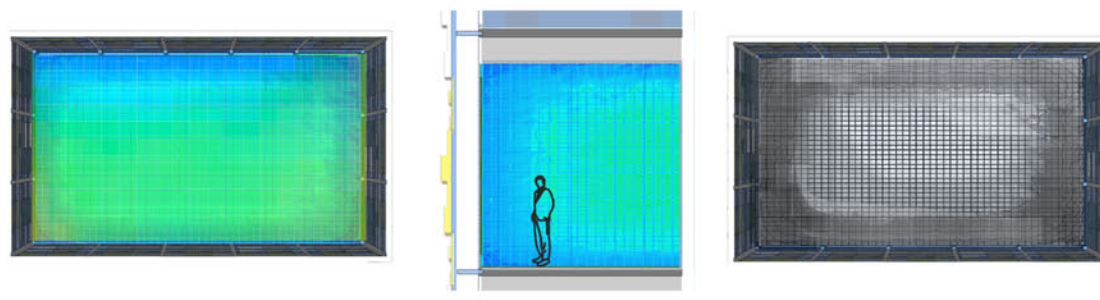


Figure 104: CFD analysis and Cell pressures: Winter months

Thermal Comfort Analysis

With the rectangular module (ANGLE) design, the radiant temperatures within the space are within a small band of values, and lie within the comfort range. Boundary condition shows an upper range of temperatures along the facade edge. The lowermost graph indicates the reason why this occurs: as a result of conduction heat gains. Material changes to lower U-values and incorporation of thermal mass along the facade would help increase thermal comfort and distribute temperatures evenly through the interior (Fig.105).

Thermal Comfort
Mean Radiant Temp
Value Range: 6.3 - 86.3 °C
• ECOTECT v8

°C

86.3+
78.3
70.3
62.3
54.3
46.3
38.3
30.3
22.3
14.3
6.3

Temperatures (0 - 90 deg.C range)

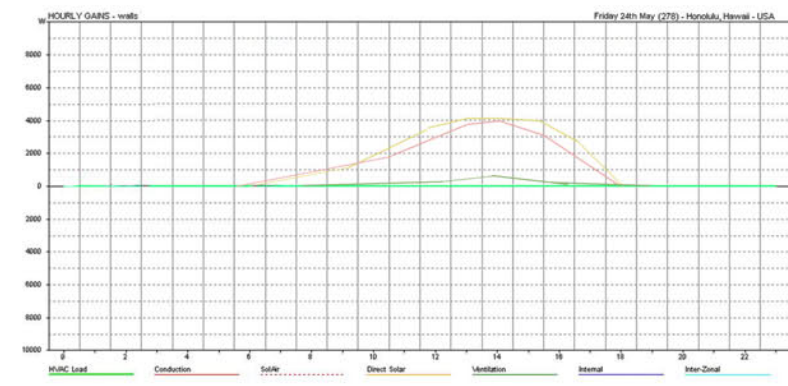
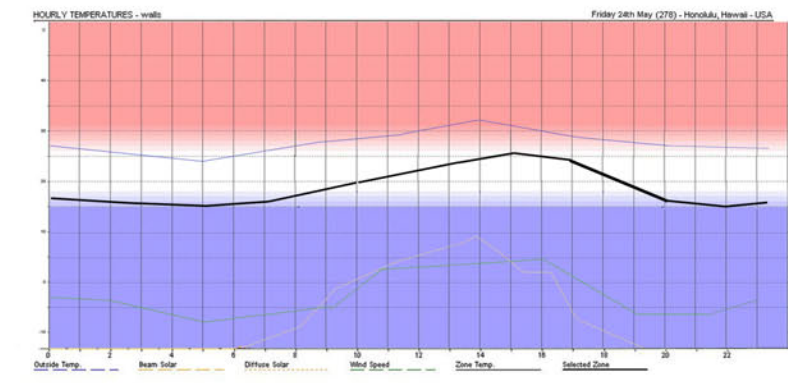
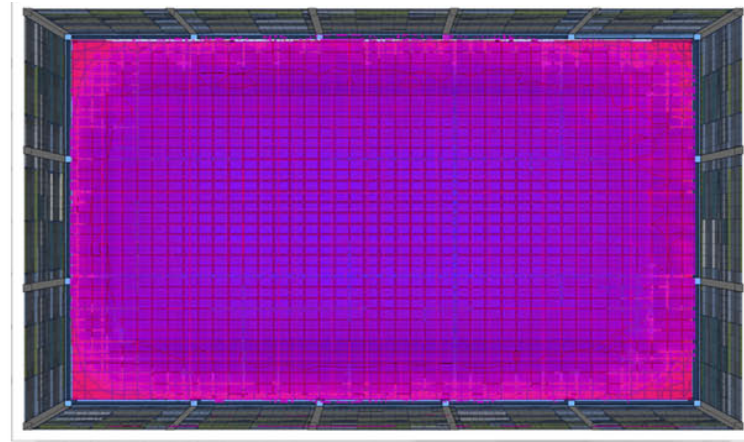


Figure 105: Thermal analysis: RECTANGLE design module

[B] Design Module (ORGANIC)

Daylighting Analysis

Summer solstice, June 21: The daylighting levels here were found to be inadequate, particularly during the summer season (Figs. 106-108). Edge conditions had spillover areas, which displayed low light levels (at times below 150 lux), not conducive for the office workplace. This inconsistency of values within the interior space can be attributed to poor adaptation of the design module to the exterior environmental lighting.

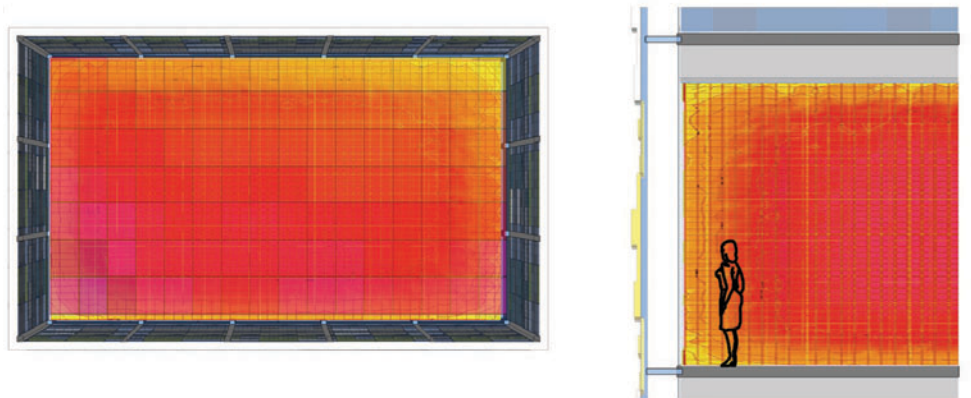


Figure 106: Summer Solstice (June 21); Morning (9:00am)

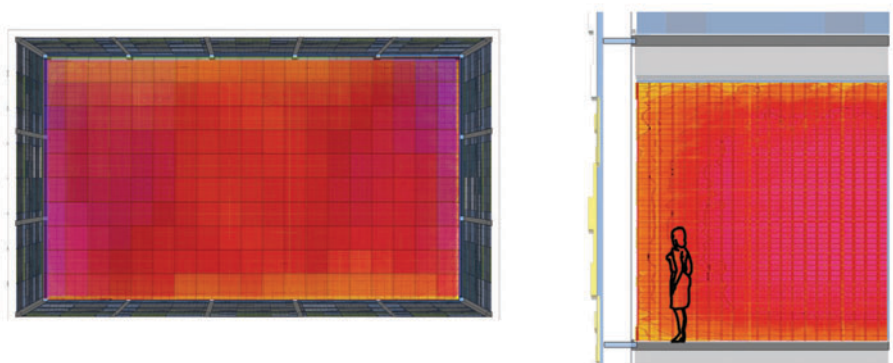


Figure 107: Summer Solstice (June 21); Noon (12:00pm)

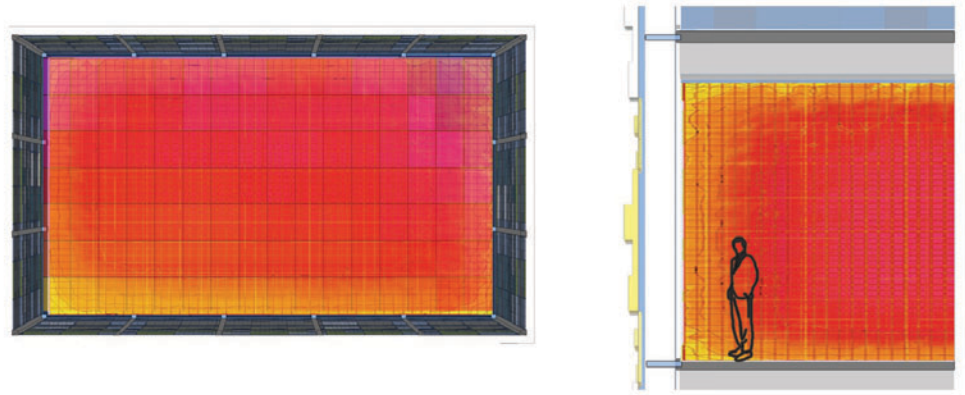


Figure 108: Summer Solstice (June 21); Evening (5:00pm)

Spring and autumn equinoxes (March 21 and September 21): The average lighting values and levels during this season were found to be moderately higher, when compared to the summer light levels. However, the edges where the solar path was away from the façade, experienced some minimal “dark spots”, in contrast to the “light spots” on the opposite northern façade edge. Despite this, the edge conditions were quite bright compared to the rest of the interior space (Figs.109-111).

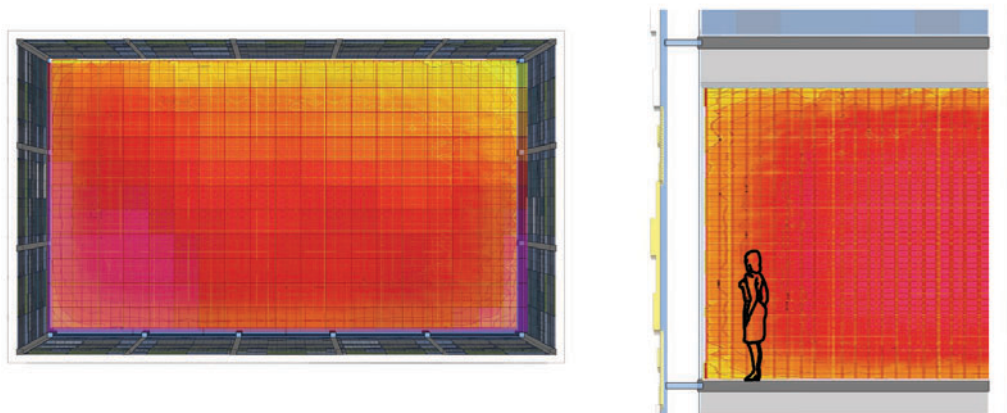


Figure 109: Equinox (March/ September 21); Morning (9:00am)

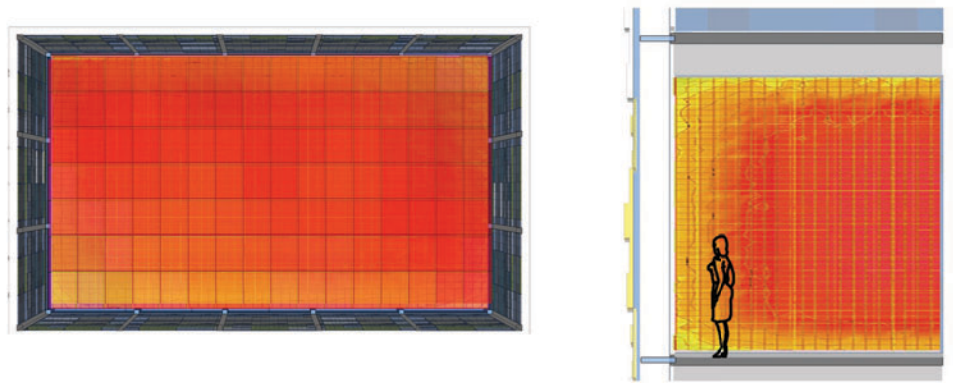


Figure 110: Equinox (March/ September 21); Noon (12:00pm)

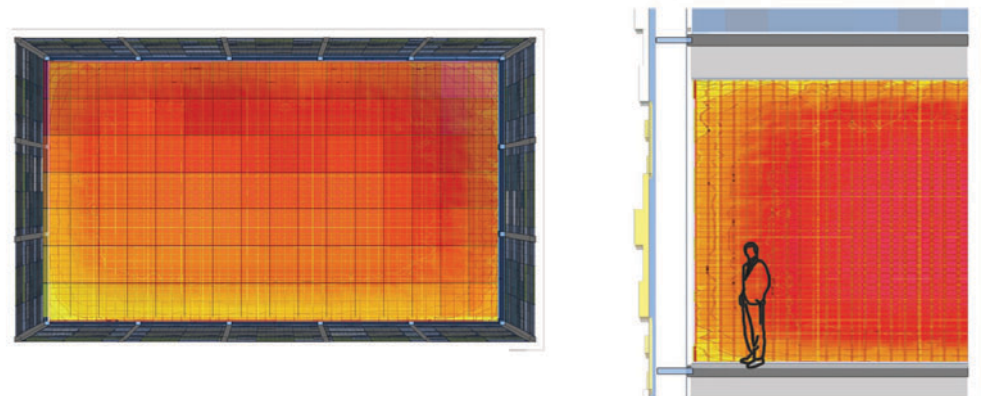


Figure 111: Equinox (March/ September 21); Evening (5:00pm)

Winter solstice, December 21: This is when the sun is at its southernmost position in the sky along the sun path diagram. At noon, it is at the lowest altitude angle (45 deg vertical from the horizon). At these very low angles, there is excess natural lighting levels (as seen in these diagrams), particularly around midday.

As seen in the analysis below (Figs.112-114), the same conditions were seen (the stark contrast between the well-lit and poorly-lit interior spaces), with the change being the increase in light levels compared to the other seasons.

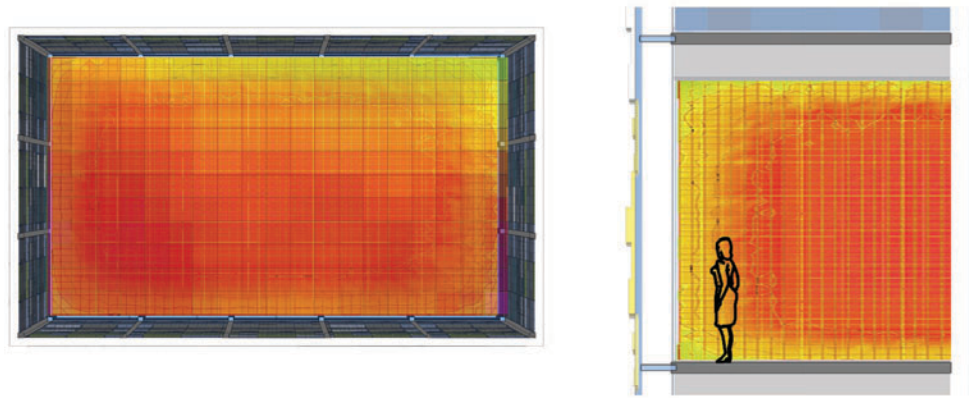


Figure 112: Winter Solstice (December 21); Morning (9:00am)

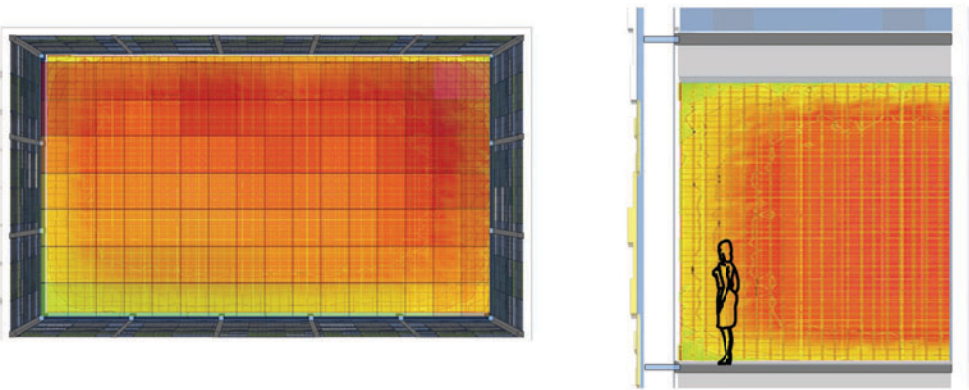


Figure 113: Winter Solstice (December 21); Noon (12:00pm)

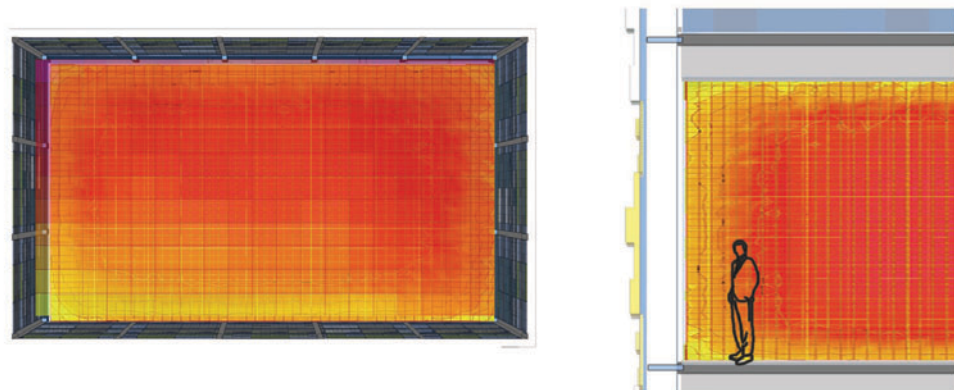


Figure 114: Winter Solstice (December 21); Evening (5:00pm)

CFD Analysis

The organic module (POROSITY) design displays, as seen in these analysis diagram (Figs.115, 116), a relatively higher range of velocities than those seen with the rectangular module design. This is certainly accountable due to the fact that the opening pores are not completely closed in the simulation, thus facilitating easier entry for the airflow into the interior spaces. However, the cell pressures are not as starkly contrasted as seen in some of the interior spots with the rectangular module, which is turn likely due to the ease of “cross ventilation” with this design.

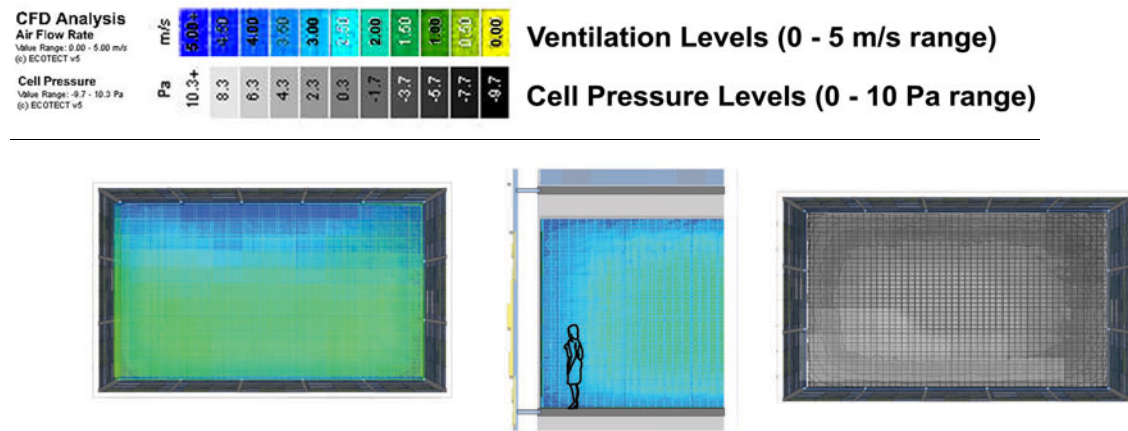


Figure 115: CFD analysis and Cell pressures: Summer months

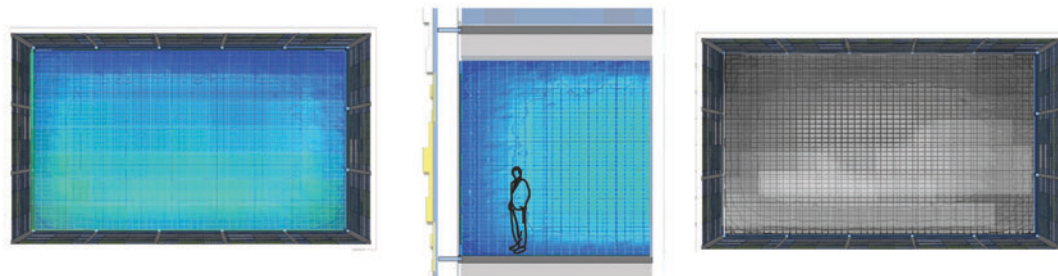


Figure 116: CFD analysis and Cell pressures: Winter months

Thermal Comfort Analysis

The organic module (POROSITY) design is similar to the rectangular module design; however, due to the increased porosity of the facade, there is a visible increase in the maximum temperature (around 3:00pm) on the peak hottest day of the year. As seen in the passive heat gains graph on the bottom, this is due in part to the heat gain caused by the materials used (conduction), and also due to the heated air traveling from the exterior to the space within (ventilation) (Fig.117).

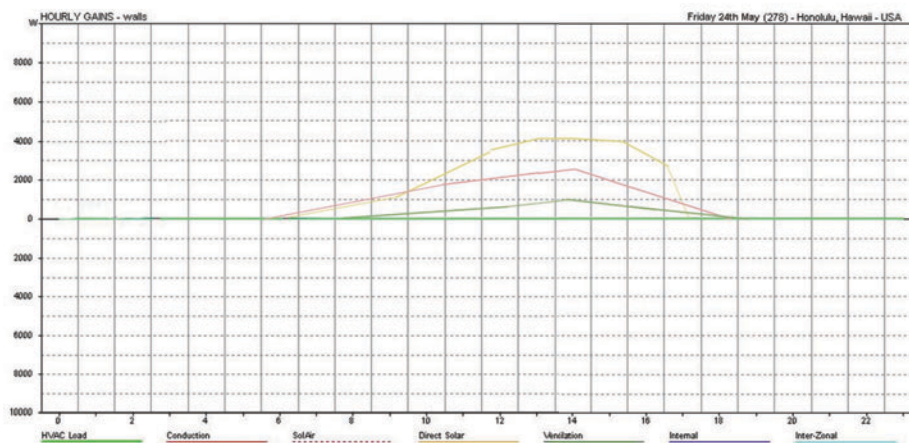
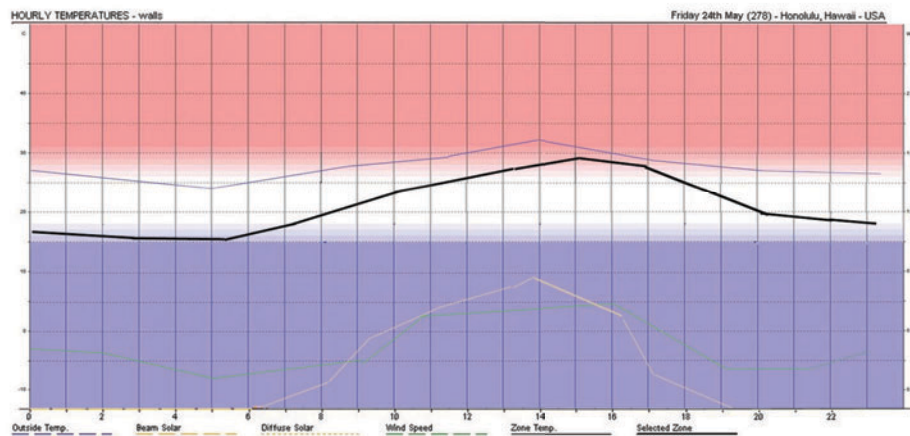
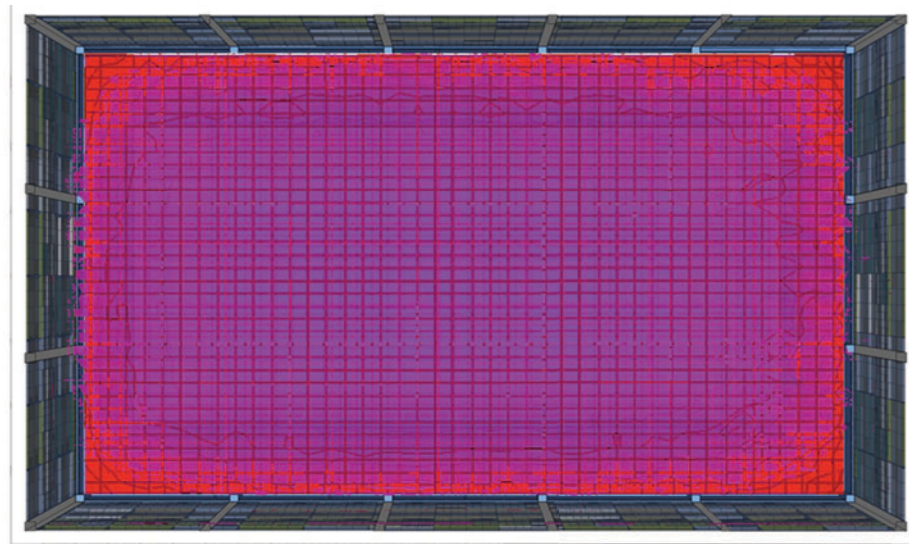
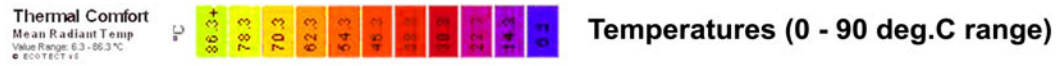


Figure 117: Thermal analysis: ORGANIC design module

[AB] Design Module (HYBRID)

Daylighting Analysis

Summer solstice, June 21: This is when the sun is at its northernmost position in the sky along the sun path diagram. At noon, it is at the highest altitude angle (91 deg vertical from the horizon). As seen from the facade daylighting simulations (Figs.118-120), the sun rays do not directly penetrate glaringly into the interior of the building space; furthermore, the daylighting levels appear to be quite adequate for the office spaces within.

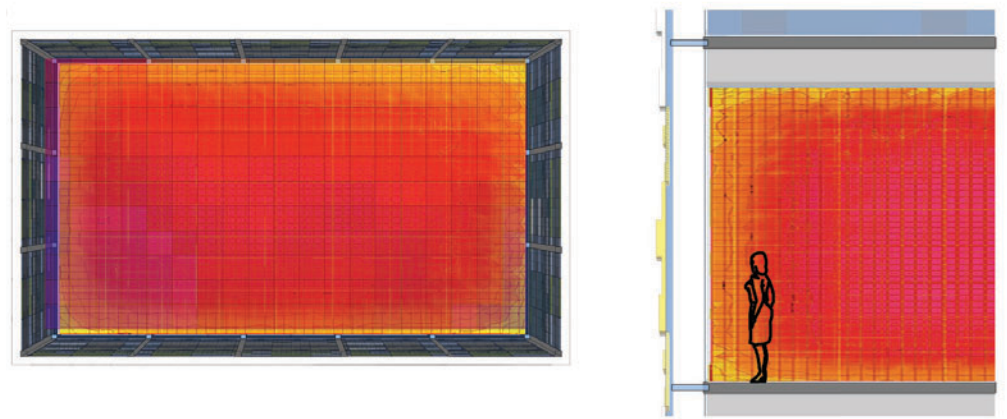


Figure 118: Summer Solstice (June 21); Morning (9:00am)

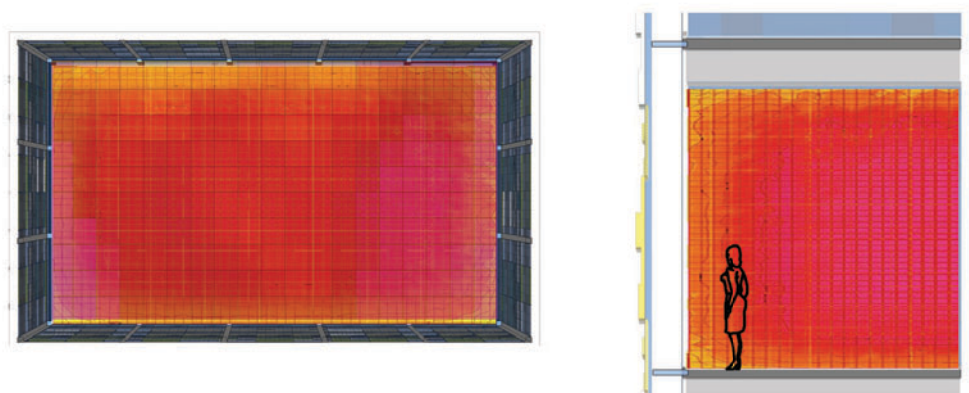


Figure 119: Summer Solstice (June 21); Noon (12:00pm)

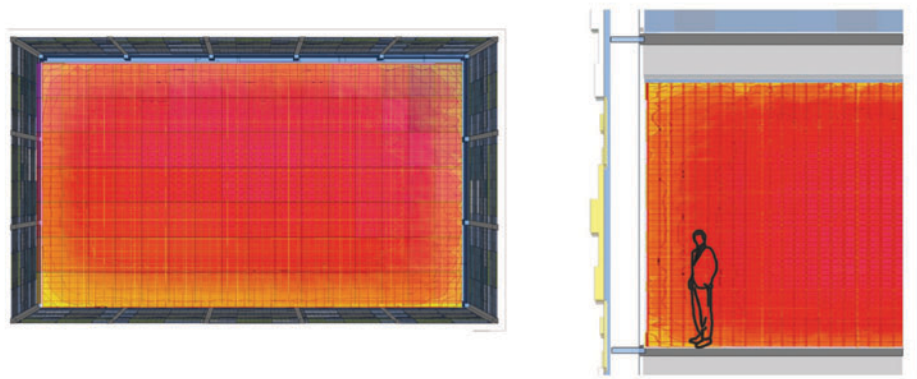


Figure 120: Summer Solstice (June 21); Evening (5:00pm)

Spring and autumn equinoxes (March 21 and September 21): The light reaching the interiors is similar to that seen in the rectangular module; however, the transitions are more gradual and so the visual comfort of the interior space within the office environment was found to be ideal (Figs. 121-123).

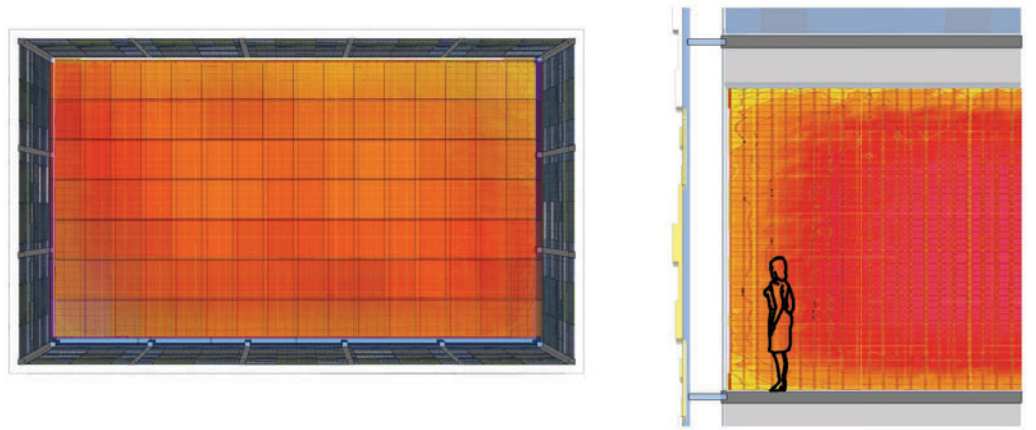


Figure 121: Equinox (March/ September 21); Morning (9:00am)

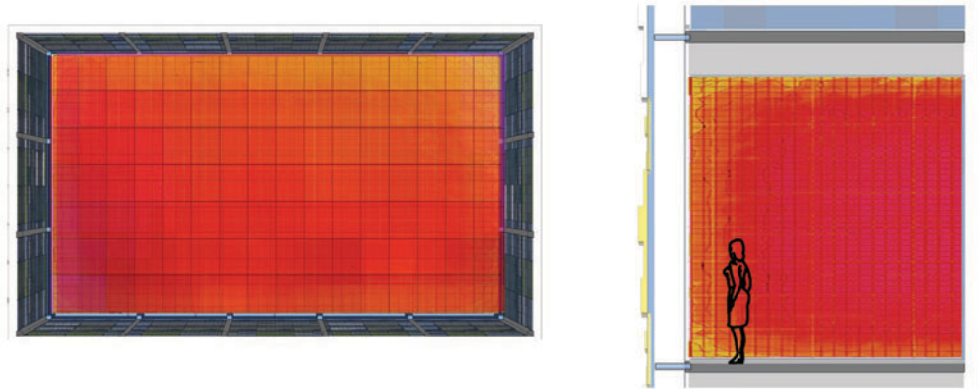


Figure 122: Equinox (March/ September 21); Noon (12:00pm)

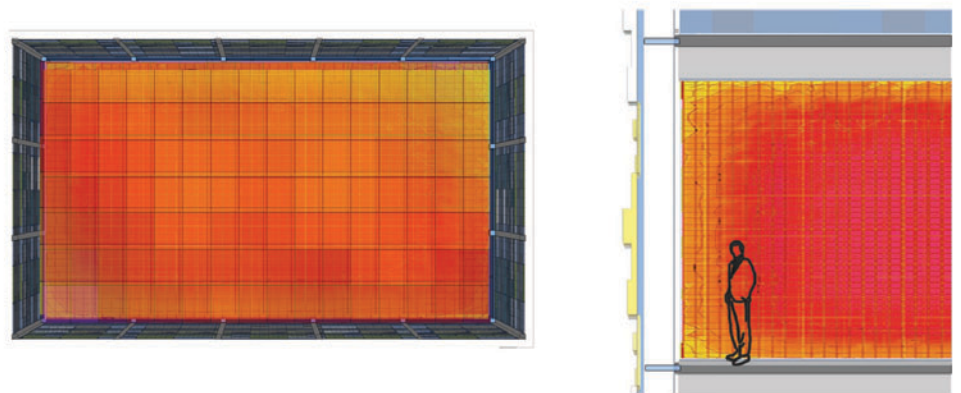


Figure 123: Equinox (March/ September 21); Evening (5:00pm)

Winter solstice, December 21: At these very low angles, there is still ideal natural lighting levels maintained throughout the space (as seen in these diagrams), particularly around midday. For the hybrid module during the winter, however, the lighting stays gradual and the transition avoids any edge “bright spots” effects and instead creates a more uniform lighting level throughout the space (Figs. 124-126).

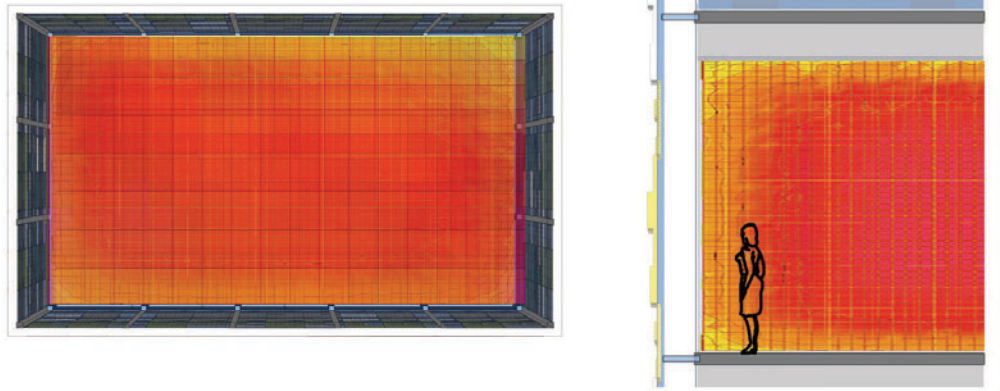


Figure 124: Winter Solstice (December 21); Morning (9:00am)

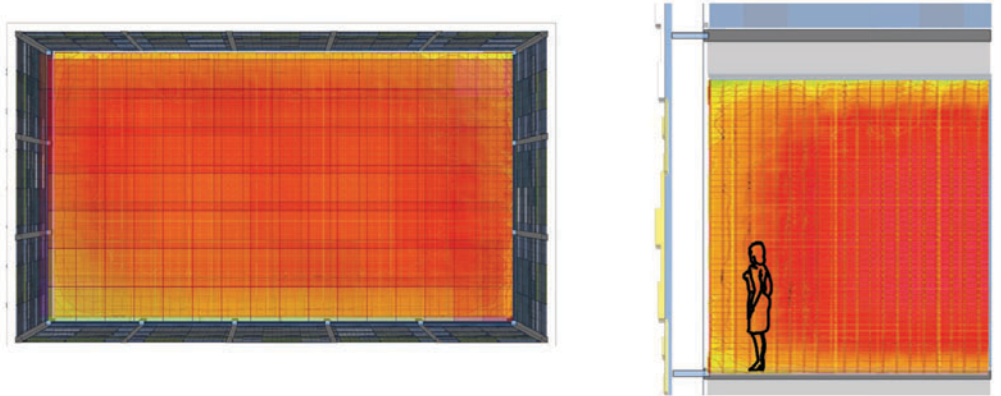


Figure 125: Winter Solstice (December 21); Noon (12:00pm)

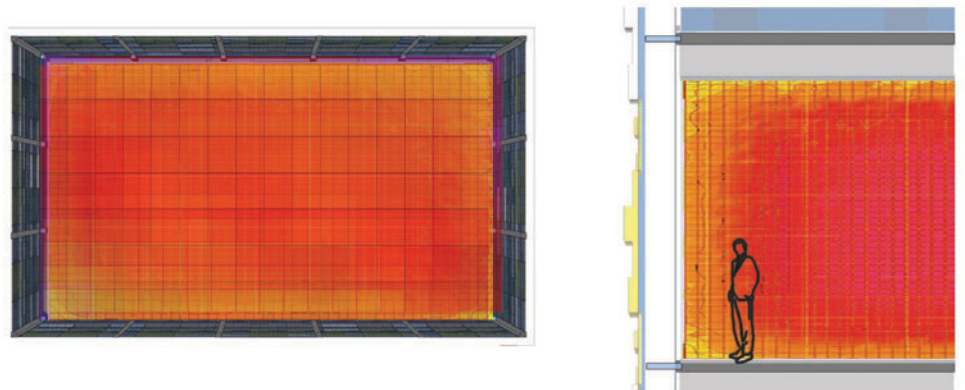


Figure 126: Winter Solstice (December 21); Evening (5:00pm)

CFD Analysis

The hybrid design, featuring a combination of ANGLE and POROSITY enhancements in the modular assembly, exhibits a smoother transition between the high and low velocity and pressure areas within the building space. Velocities are kept to a comfortable 1.0 to 2.5 m/s, and cells pressure “hot spots” are effectively nonexistent (Figs. 127, 128).

There is not too much difference between summer and winter months, excepting reduced cell pressures on the southern facade during the winter season.

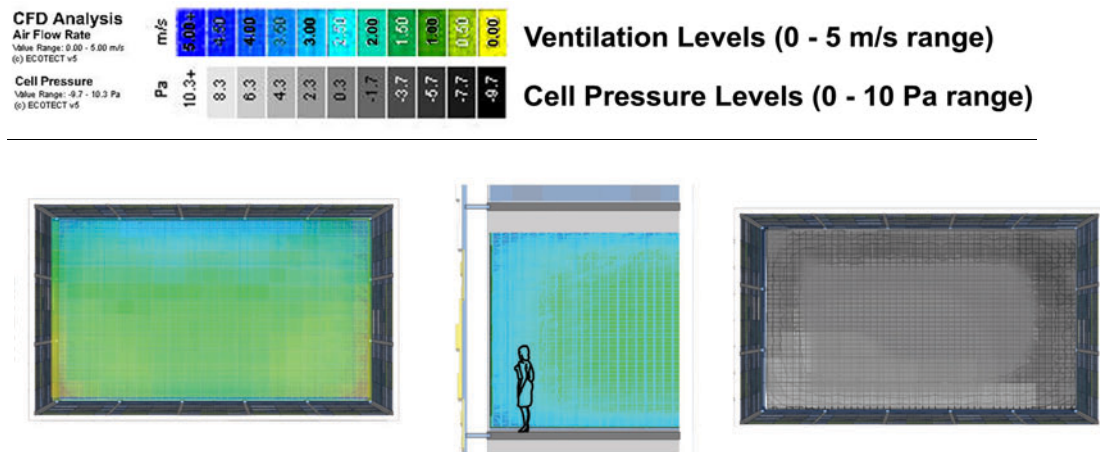


Figure 127: CFD analysis and Cell pressures: Summer months

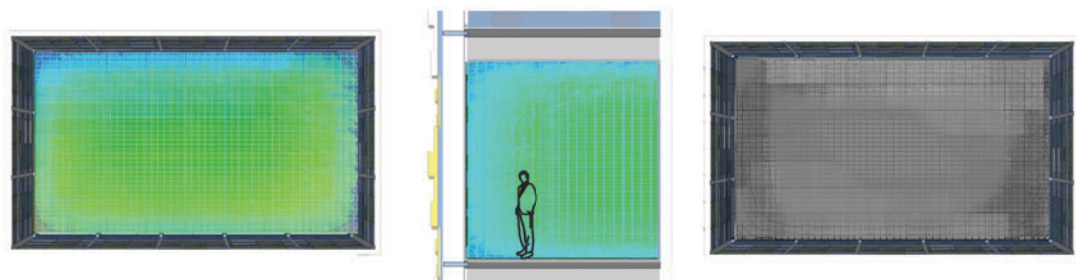


Figure 128: CFD analysis and Cell pressures: Winter months

Thermal Comfort Analysis

The hybrid design, truly seems to excel in the thermal aspect of the design performance. First, the temperatures are within the comfort range, similar to the rectangular module design, with the addition of a gradual thermal heating and cooling through the day. This is also clearly visualized in the heat gains breakdown, where the solar radiation and conduction contribute to lower heat gains, even on the peak hottest day, during mid-afternoon (Fig.129).

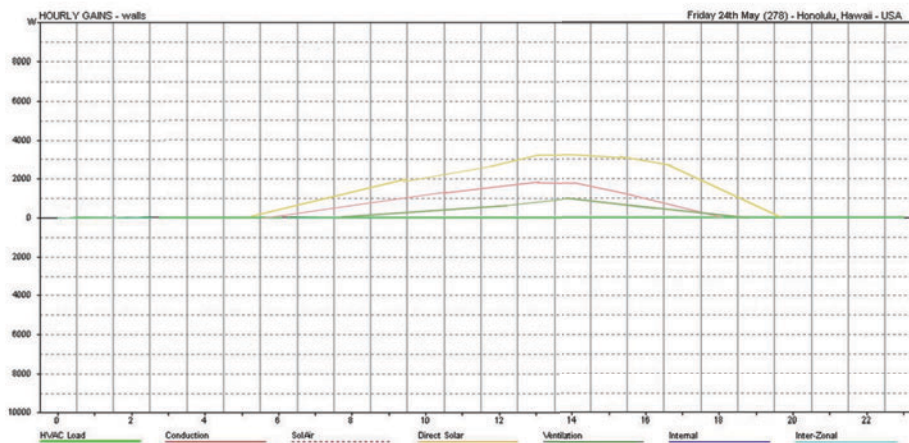
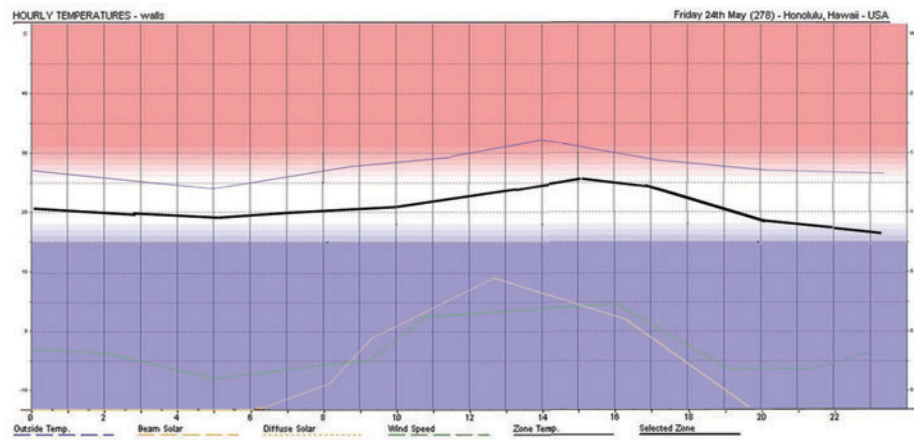
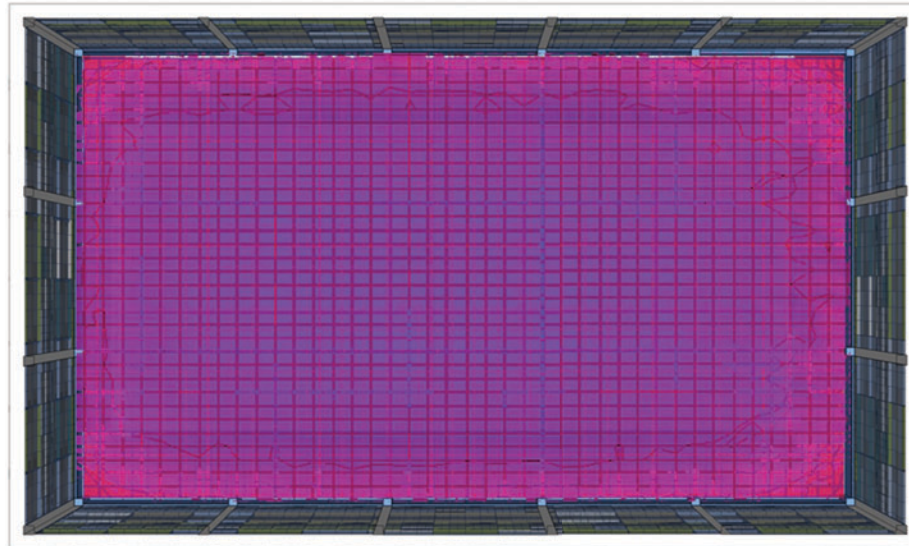
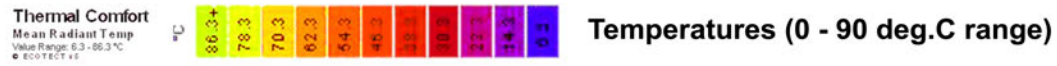


Figure 129: Thermal analysis: HYBRID design module

Figure 130: Daylighting Analysis Matrix (Rectangular Module = A)

Figure 131: Daylighting Analysis Matrix (Organic Module = B)

Figure 132: Daylighting Analysis Matrix (Hybrid Module = AB)

Figure 133: CFD Analysis Matrix (Modules = A, B, and AB)

Figure 134: Thermal Analysis Matrix (Modules = A, B, and AB)

4.4 BIOPHILIA: Analysis and Discussion

The two sub-groups (X and Y) were markedly different in their responses to the images (stimuli) presented.

For sub-group X: The majority of preferences pointed to strong significance in stimulus image type (Hybrid [AB] > Rectangular [A] > Organic [B] > Base [O]). The results are consistent within the exterior view and the exterior elevation; however, the same modules are significantly rated differently within the interior views, with the significance being: (Organic [B] > Hybrid [AB] > Base [O] > Rectangular [A]).

For sub-group Y: The majority of preferences pointed to strong significance in stimulus image type (Hybrid [AB] > Organic [B] > Rectangular [A] > Base [O]). The results are consistent within the exterior view and the exterior elevation, as well as with the interior views.

Verbal responses/ questionnaire analysis

Overall responses were indicative of the general trend in people's preferences through the study. Out of a total of 40 respondents, the majority of 24 people (60% approx.) preferred image AB1 (*Hybrid module, exterior view*, Fig.135). 28 percent of the respondents (11 respondents) preferred the B3 (*Organic module, interior view*, Fig.136) tree. Five respondents of the 40 total (13%) preferred the A1 (*Rectangular module, exterior view*, Fig.137) (Also Figs.138, 139).



Figure 135: Hybrid module, exterior view (image AB1)



Figure 136: Organic module, interior view (image B3)



Figure 137: Rectangular module, exterior view (image A1)

Figure 138: Stimuli presented during Psychophysiology Experiments (Modules = A, B, and AB)

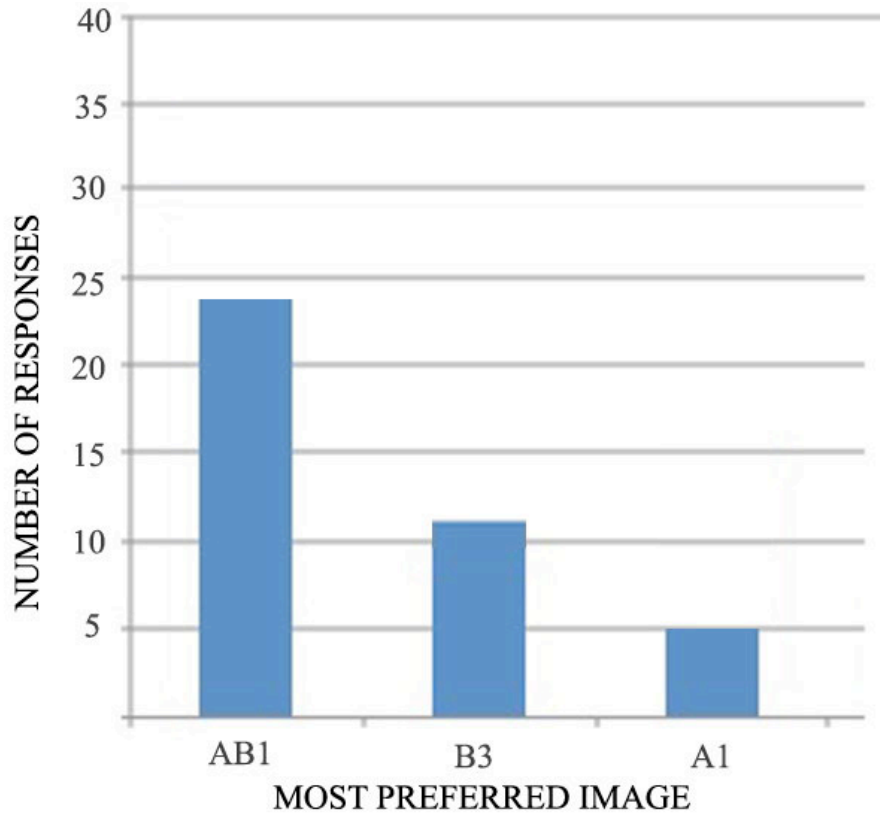


Figure 139: Most preferred images among all respondents

When questioned about the particular attributes that they preferred regarding the selected images, the responses were highly consistent with two of three images.

AB1 Attribute Selection (Sub-group X): For image AB1, a number of respondents (8 respondents, 40%) cited “Nature Nostalgia” to be the primary reason that they preferred the image. They also stated that the colors and the forms had them associating the building to natural processes and stretchy materials. Secondly, the attribute “Interesting Aesthetics” was popularly voted on as well (6 respondents, 30%). “Comfortable Environment” (3 respondents, 15%) and “Dynamic/Kinetic Module” (3 respondents, 15%) attributes were both placed equally. It stands to reason that since this was the sub-group without any previous design knowledge about the researcher’s intent and concept, they voted purely based on the aesthetic aspects and visual comfort of the image (Fig. 140).

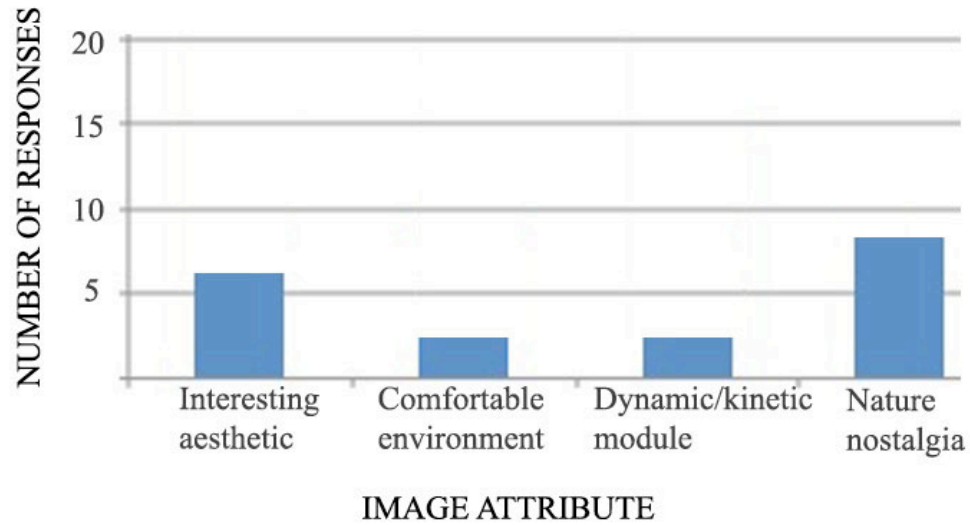


Figure 140: Sub-group X: Attribute Preference for AB1

AB1 Attribute Selection (Sub-group Y): When surveyed about the image within sub-group Y, a majority of them (12 respondents, 60%) cited “Dynamic/Kinetic Module” as being key to achieving the design intent, while a second majority of votes went to the “Nature Nostalgia” attribute (5 respondents, 25%), for the design’s responsiveness to the daylighting and ventilation. “Comfortable Environment” was placed third (2 respondents, 10%), while “Interesting Aesthetics” garnered little attention within sub-group Y (1 respondent, 5%), and clearly not as much as within sub-group X. This sub-group was well aware of the design process and the functioning behind the hybrid module, and these qualities provided them with the attribute selection (Fig.141).

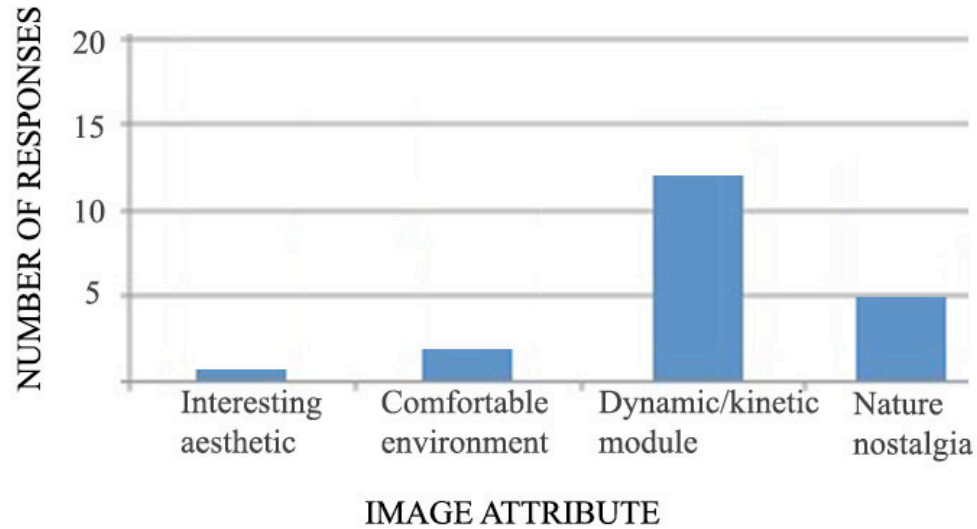


Figure 141: Sub-group Y: Attribute Preference for AB1

Overall responses for Image AB1: As indicated in the figure below, the overall responses among respondents was quite clear, as to the nature of the selection process. Most of the respondents felt that the organic design module displayed characteristics evocative of natural functions and also was visually pleasing and comfortable (Fig.142).

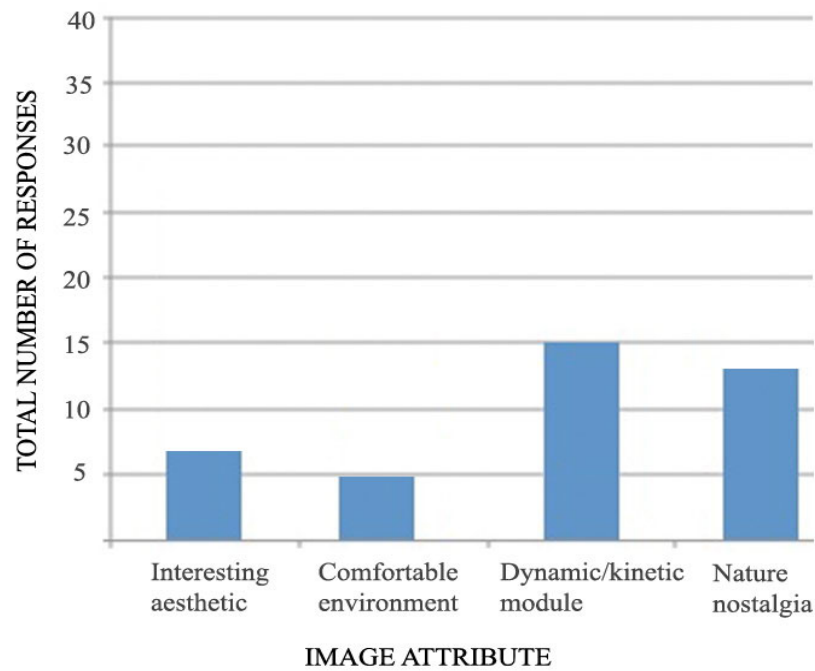


Figure 142: Total responses (X & Y): Attribute Preference for B3

B3 Attribute Selection (Sub-group X): For image B3, one half of the respondents (10 respondents, 50%) cited “Comfortable Environment” to be the primary reason that they preferred the image. Furthermore, the “Nature Nostalgia” attribute was selected by a number of respondents as well (8 respondents, 28% approx.), while the least selected attributes were the “Dynamic/Kinetic Module” (1 respondent, 5%) and “Interesting Aesthetics” (1 respondent, 5%). This was the group that was not previously updated regarding the original design intent of the organic design module, or the complexities in the materials and functioning (Fig.143).

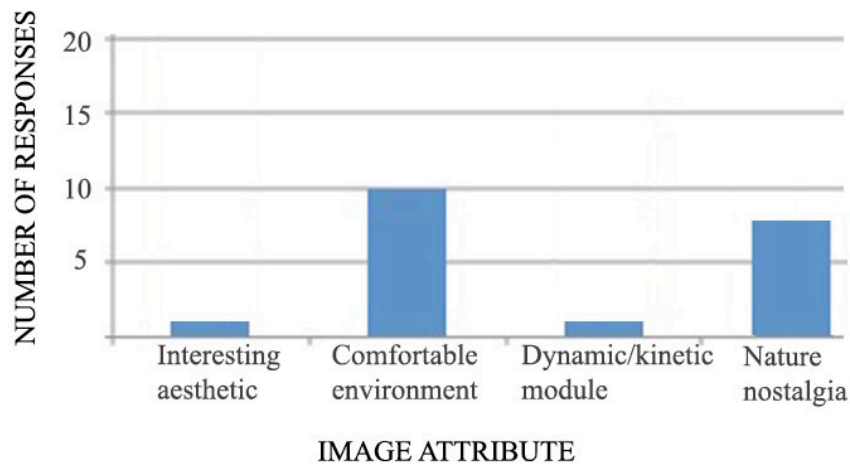


Figure 143: Sub-group X: Attribute Preference for B3

B3 Attribute Selection (Sub-group Y): Within this sub-group, the respondents were very clear. A majority of them (9 respondents, 45%) cited “Nature Nostalgia” as their main justification for selecting the B3 image. “Comfortable Environment” was the second placed attribute (6 respondents, 30%), while “Dynamic/Kinetic Module” took some votes (3 respondents, 15%). “Interesting Aesthetics” placed last in their list of attributes (2 respondents, 10%). Since this sub-group was well aware of the design process and the concept that led to the organic module design, it was a relevant justification for their selection process as a result (Fig.144).

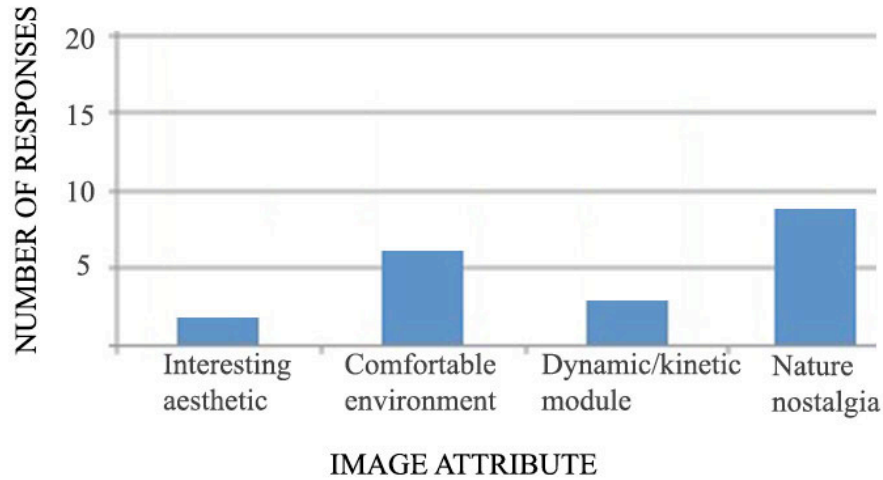


Figure 144: Sub-group Y: Attribute Preference for B3

Overall responses for Image B3: Most of the respondents stated that the organic module reminded them of natural functions and organism-like structures. They were highly encouraging of the design intent, and revealed also that the image was very porous and “screen-like”, within the building view. The lighting quality was something they appreciated; furthermore, they did respond that the views were less “cage-like”, although more obstructed than the base image and the other images of the interior views (Fig.145).

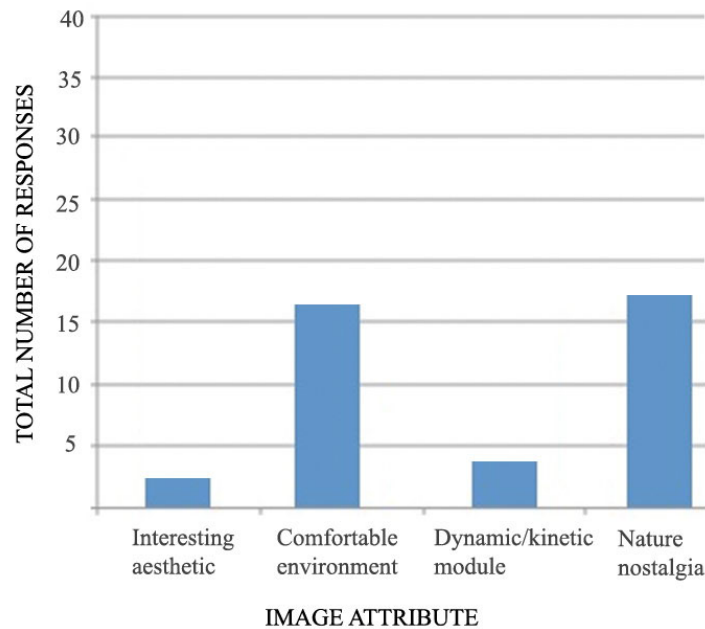


Figure 145: Total responses (X & Y): Attribute Preference for B3

A1 Attribute Selection (Sub-group X): For image A1, the majority of respondents (12 respondents, 60%) cited “Interesting Aesthetics” to be the primary reason that they preferred the image. Other attributes selected were “Comfortable Environment” (4 respondents, 20%) and “Dynamic/Kinetic Module” (3 respondents, 15%), while the least selected attribute was the “Nature Nostalgia” (1 respondent, 5%). Thus, while respondents clearly maintained that the image evoked associations with the look, feel, and overall environmental visual comfort, they were unable to view the association with nature (Fig.146).

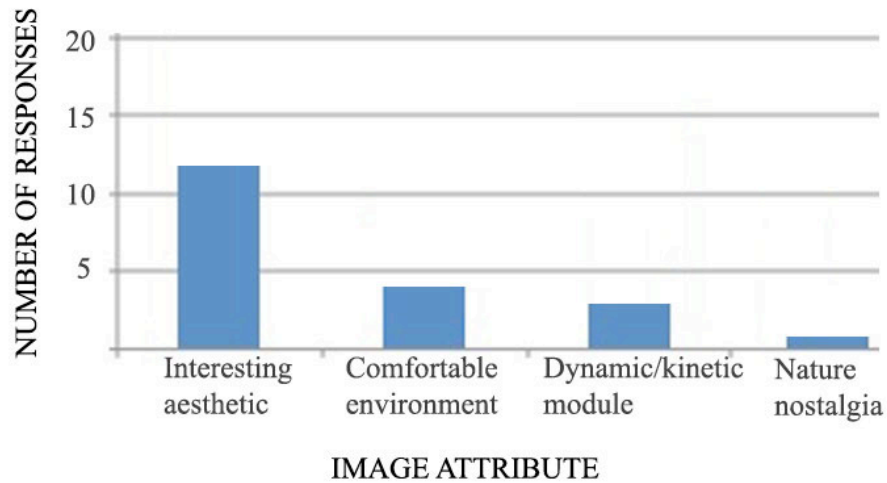


Figure 146: Sub-group X: Attribute Preference for A1

A1 Attribute Selection (Sub-group Y): Here, one half of the respondents (10 respondents, 50%) cited “Comfortable Environment” to be the primary reason that they preferred the image. Other attributes selected were “Dynamic/Kinetic Module” (7 respondents, 35%) and “Interesting Aesthetics” (3 respondents, 15%). None of the respondents selected “Nature Nostalgia” as a deciding attribute for his or her selection of image A1. Again, although the image proved to be a successful indicator of a comfortable visual and dynamic nature, the association with nature was absent, even after the researcher’s design intent was clearly explained to the respondents (Fig.147).

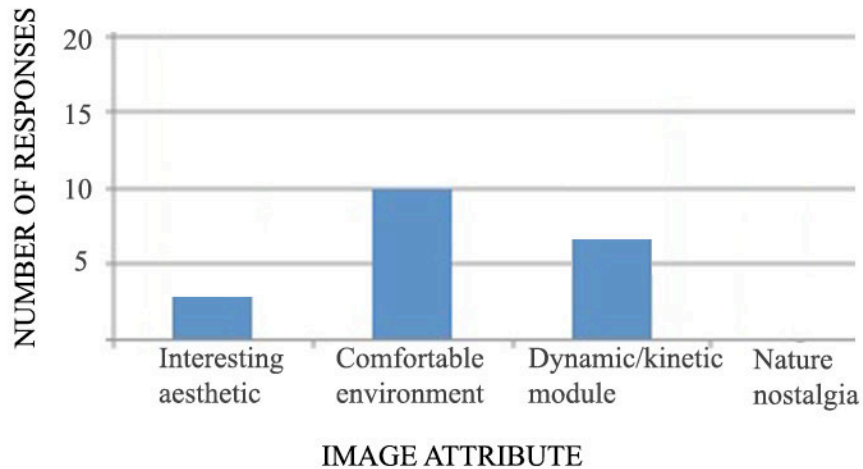


Figure 147: Sub-group Y: Attribute Preference for A1

Overall responses for Image A1: The overall responses among respondents were a clear indicator as to the rectangular module's non-organic form and aesthetic. While the nature nostalgia component was almost evidently absent from the responses, the fact remains that this module's design characteristics were appreciated for its dynamism and responsiveness to the environment, in order to achieve a comfortable indoor working environment (Fig.148).

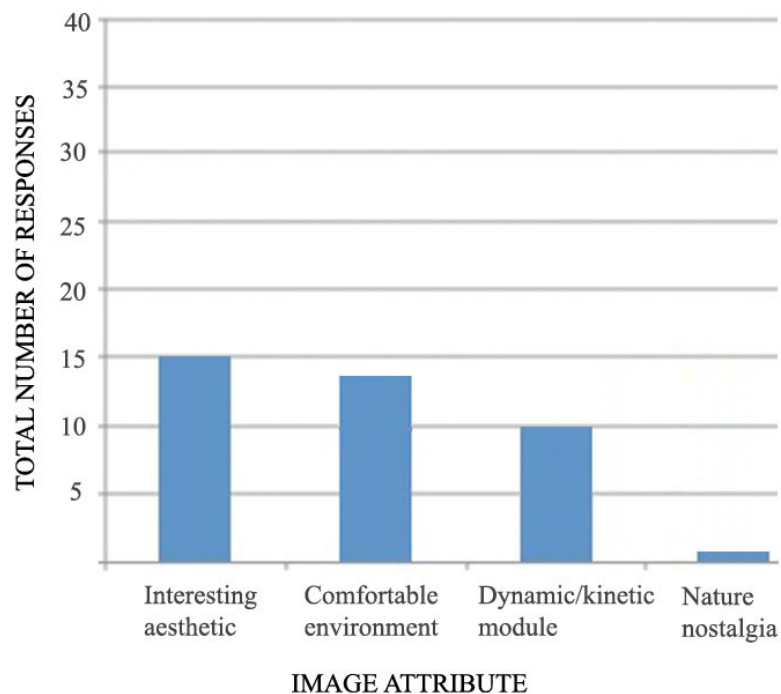


Figure 148: Total responses (X & Y): Attribute Preference for A1

Survey Results, Additional notes: There was no significant difference in responses between vegetated and non-vegetated imagery. Since sub-group X was not briefed prior to the start of the experiment, the lack of knowledge is the probable cause for this trend that is different from that in sub-group Y; in the latter case, the respondents were well aware of the technologies and materials that served as the “backstory” to the imagery.

(A) Heart Rate change (ECG)

Module Design Type (O, A, B, AB) in each category was tested against the baseline physiological response for every participant/respondent.

From the heart rate analysis (see Table 5, Figure 149), it is evident that the ECG measured among the 40 respondents exhibit the following mean trends:

- 1) Significant difference ($P < 0.05$) between BASE Module and RECTANGULAR, ORGANIC, HYBRID Module types.
- 2) Significant difference ($P < 0.05$) between RECTANGULAR and ORGANIC, HYBRID Module types.
- 3) BASE Module (O1 exterior view, O2 elevation) imagery elicited the strongest increase in value changes (degree of activation and orientation) compared to baseline activity/data (see Tables XIV, XV). This indicates that these images were highly arousing and prone to stimulus rejection, probably due to the unfamiliarity of the design images, or due to the stark nature of the images.
- 4) Both sets of Organic Module imagery (B1, B2, B3) and Hybrid Module imagery (AB1, AB2, AB3) caused a corresponding decrease in heart rates, compared to baseline activity of the respondents. This decrease was stronger for the Organic Module images, indicating that the stimuli presented were quite calming and also tended to focus the viewer’s attention.

This analysis indicated that the effect of module type differences on the heart rate responses was significant (Fig.149).

Img_type	Estimate	Error	DF	t Value	Pr > t
O	0.0628	0.4631	81	1.78	0.05517
A	-0.0155	0.4676	81	-1.39	0.2064
B	-0.614	0.4614	81	-0.45	<0.00015
AB	-0.0402	0.4618	81	-0.68	0.4676

Table 5: Mean ECG estimates and Std. of error

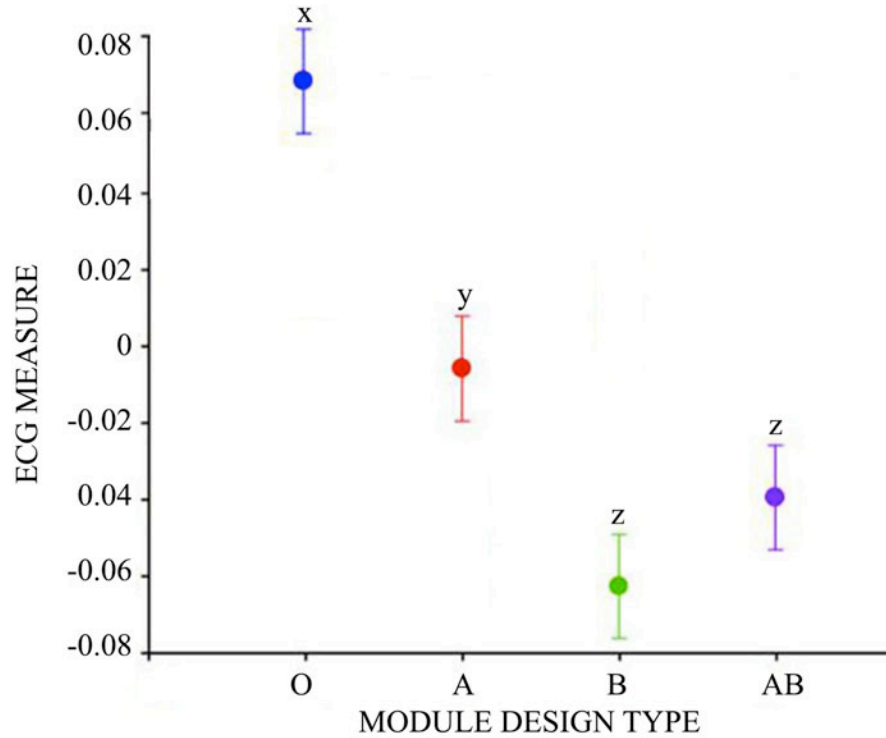


Figure 149: Mean (\pm SE) ECG response to different module types

(Note. Data points with different letters indicate statistically significant difference ($P < 0.05$))

(B) Brain alpha activity and change (EEG)

Module Design Types (O, A, B, AB) in each category was tested against alpha brain activity responses among the 40 respondents, similar to other physiological measures. From the analysis performed, it was observed that the changes in response between the baseline and the design modules were found to be very significant, with both the Hybrid module and Rectangular module in particular. The greater the alpha activity, the larger was the indication of calmness and “wakeful relaxation” among the respondents, further indicating evidence of the fact that the respondents viewed the dynamic forms (Hybrid module, Rectangular module) to be more

relaxing than the static forms (Organic module, Base module).

“EEG Left” results revealed the following trends in measures (Table 6, Fig.150):

- 1) Significant difference ($P < 0.05$) between BASE Module and ORGANIC, HYBRID Module types.
- 2) Significant difference ($P < 0.05$) between RECTANGULAR and ORGANIC, HYBRID Module types.

Img_type	Estimate	Error	DF	t Value	Pr > t
O	-0.2376	0.1503	81	-0.25	0.4192
A	-0.1736	0.1515	81	-0.69	0.4466
B	0.1581	0.1514	81	0.32	0.8537
AB	0.2674	0.1522	81	0.77	0.6401

Table 6: Mean EEG (Left) estimates and Std. of error

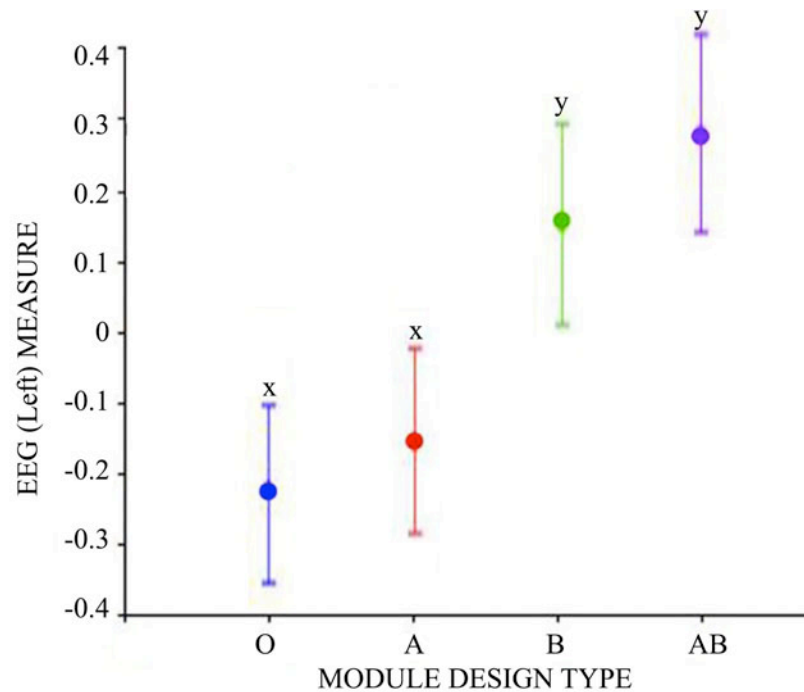


Figure 150: Mean (\pm SE) EEG (Left) response to different module types

(Note. Data points with different letters indicate statistically significant difference ($P < 0.05$))

“EEG Right” results revealed the following trends in measures (Table 7, Fig.151):

Significant difference ($P < 0.05$) between BASE Module and RECTANGULAR, ORGANIC, HYBRID Module types.

Img_type	Estimate	Error	DF	t Value	Pr > t
O	-0.1359	0.2234	81	-0.19	0.0057
A	0.6280	0.2339	81	0.37	0.3953
B	1.642	0.2217	81	0.95	0.8094
AB	1.205	0.2313	81	0.22	0.2769

Table 7: Mean EEG (Right) estimates and Std. of error

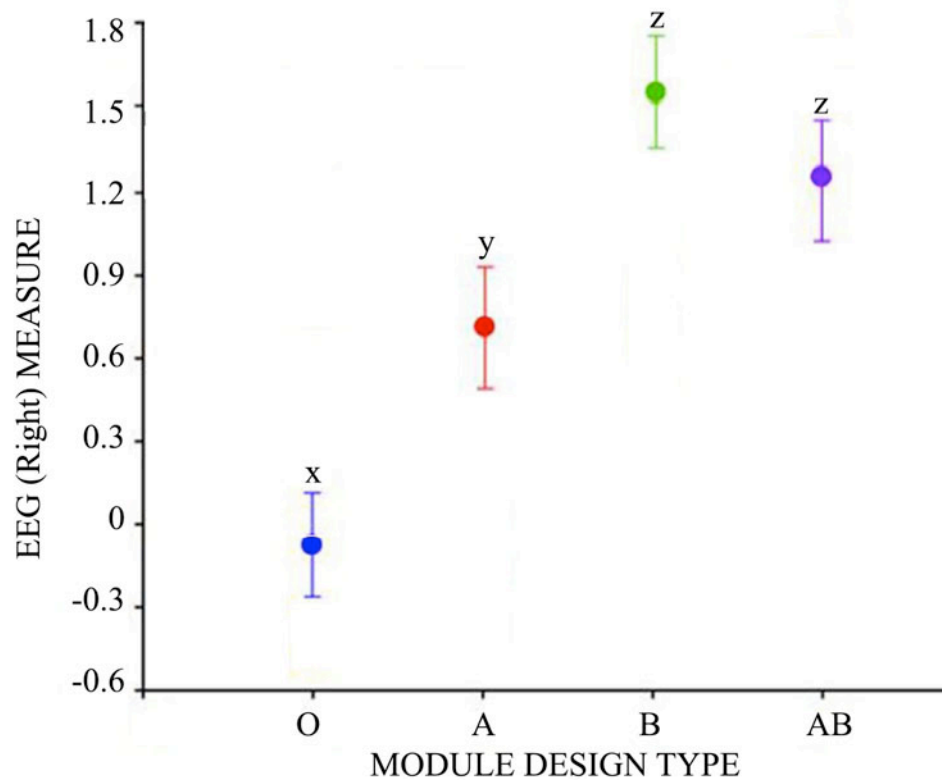


Figure 151: Mean (\pm SE) EEG (Right) response to different module types

(Note. Data points with different letters indicate statistically significant difference ($P < 0.05$))

(C) Facial muscular activity and “Smile” response (EMG)

Another significant change in measure was found in the electromyography results, especially from the “smile” measure. Module Design Types (O, A, B, AB) in each category was tested for facial muscular activity responses among the 40 respondents.

Facial muscular activity in humans is measured in a variety of ways, and this research utilized three measures:

- 1) EMG c: which is an indicator of corrugator muscular activity
- 2) EMG o: which is an indicator of orbicularis muscular activity
- 3) EMG z: which is an indicator of zygomatic muscular activity

The combination of EMG o and EMG z yields a measure of a “smile”. This “smile” measure is an indicator of the action potential caused by pleasure and is therefore a sign of genuine positive affective measure. Easy to measure from normal baseline activity, the greater the EMG activity, the larger is action potential among the respondents, which displays evidence of the fact that the respondents viewed the Hybrid and Rectangular modules to be more pleasurable than the Base and Organic modules. There was also a marked significance between the Organic module and the other design modules, as indicated by the preference order:

Hybrid (AB) > Rectangular (A) > Organic (B) > Base (O).

“EMG Smile (o and z combined)” results revealed the following trends in measures (Table 8, Fig.152)

- 1) Significant difference ($P < 0.05$) between BASE Module and ORGANIC, HYBRID Module types.
- 2) Significant difference ($P < 0.05$) between ORGANIC and HYBRID Module types.

Img_type	Estimate	Error	DF	t Value	Pr > t
O	73.0954	5.1101	81	0.85	0.5635
A	92.1628	4.9056	81	0.08	0.4209
B	85.3213	4.9934	81	0.39	0.5221
AB	101.989	4.8097	81	0.26	0.3740

Table 8: Mean EMG (Smile) estimates and Std. of error

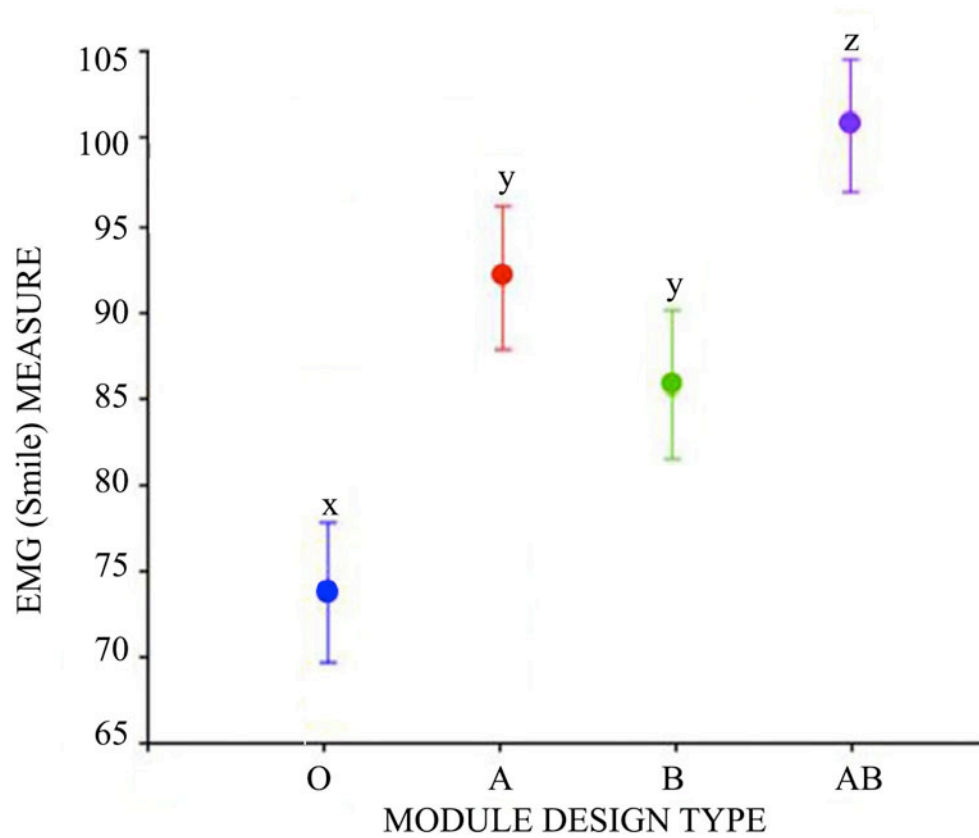


Figure 152: Mean (\pm SE) EMG (Smile) response to different module types

(Note. Data points with different letters indicate statistically significant difference ($P < 0.05$))

4.5 RESULTS AND CONCLUSIONS

4.5.1 Conclusions on Biomorphism

Biomorphism: Initial Hypothesis and Summary

“Learning from cues found in Nature – creation of responsive architecture” – is the idea that is the primary motivation behind the research focus. Taking inspiration from cross-sectional studies of the structural and hierarchical, dynamic arrangements of leaf systems found in different trees, the study approaches building performance by incorporating a modular façade system. The design analogies transferred from a leaf-to-building module are explored to determine dynamic interactions within the façade modules for an office space in the subtropics.

Two (2) main design characteristics are investigated in the biomorphic study: 1) Angle of incidence, and 2) Surface porosity. Three (3) design modules are proposed and analyzed in later sections: (a) Rectilinear, (b) Organic, and (c) Hybrid

Biomorphism: Results and Discussion

How is Biomorphism related to the overall premise of interconnectedness?

It has been proposed (and in successive sections, also proven) that the preferential and restorative responses towards natural elements and settings can be traced back and thus partly attributed to their underlying formal and nature-like characteristics. There is a clearly illustrated path, as indicated and elucidated in this thesis, of “morphing” from a biomimetic inspired nature-driven analogy to extracting the contents of this analogy and finding appropriate applications in the design realm. Thus, in conclusion, it has been established that humans show a consistent aesthetic preference for certain typical natural elements, and that these can also engender restorative responses. Humans have also been found to display an affective relationship with natural entities, by relying both on cognitive and neurological research. This combination of precognitive and cognitive affiliation for nature and natural elements has been termed “Biophilia” or the “Love of Nature”.

Additionally, it should also be noted that the (re)presentation of nature within the built environment is not the only criteria being evaluated and validated by the research.

While the research findings predominantly prove that natural design elements elicit positive emotive and affective responses, there is also a need to acknowledge that the actual integration of nature and vegetative elements will also add to the consistency of the findings. Indeed, an

investigation into a variety of vegetation samples and testing them against the findings established in this dissertation will be an interesting thread of pursuit for future designers, and students of landscape architecture and horticulture.

4.5.2 Conclusions on Biomimicry

Biomimicry: Initial Hypothesis and Summary

Biomimetic architecture is a process that is primarily driven by inspiration from natural systems and organisms. Comprehensive simulations using environmental analysis tools and energy simulation software are performed to assess the relative benefits of the design iterations measured as building occupant comfort components: Daylighting indices (illumination in “lux”/daylight sky factor), Natural ventilation (wind direction N/S/E/W, and relative wind speeds in “m/sec”), and Thermal performance levels (temperature controls in “deg. F/deg. C”).

Designs and patterns found in nature are often resolved at the “macro” as well as at the “micro/nano” molecular levels, which prompts further investigation into present-day advancements in material science and nanotechnologies. Biomimicry and nanotechnology are ways of looking closer at systems and material structures and properties; by incorporating non-mechanical, passive material systems, the objective is to envision a future for building envelopes that is passively controlled, and leaving a positive ecological footprint.

Biomimicry: Results and Discussion

Nanotechnological applications in architecture can vary widely from early stages of design to the final touches of finishes and throughout the building's lifetime. Such novel methods and material explorations provide opportunities to move into new high value-added areas both by creating new architecture and by radically changing traditional ones. There is a need for architects, scientists and engineers to give careful thought to any ethical, cultural, architectural and environmental issues raised by nanotechnology, to say whether any new regulatory controls are required, and to enter into an open dialogue with the public. It is an opportunity we must seize, and the governments shall put in place public amenities and knowledge bases, as well as incentives for knowledge transfer and high educational standards, to enable companies to place innovation at the centre of their strategies for the development of technology.

As far as the predictions of nanotechnology's future are concerned, global trends suggest that nano is rapidly gathering and gaining momentum. Expansion in scientific research and

development, public and corporate investments, public-private partnerships, media coverage, patents, services and devices clearly indicate that nanotechnology is growing rapidly.

The aim of this materials and nanotechnology research is to bring to light the applications offered by nanomaterials in a particular sector and to examine the new materials from the point of view of architects, interior designers and designers – is the right way to encourage people to examine a new technology more closely, both critically as well as enthusiastically, particularly when they would otherwise be unlikely to discover the field through scientific publications on nanosciences and technologies.

There is an intricate balance and interrelatedness between human beings and the natural and built worlds. It is up to designers and architects to recognize this inherent symbiosis and adapt, learn, and evolve from nature. It is, first and foremost, important to observe that a “bottom-up” approach, such as the one advocated by Janine Benyus (1997), and in the methodology implemented through all the phases of this dissertation, needs to translate into the physical realms of biomimetic design applications in general. If we are to move towards a more complete sustainability, the need is not only replacement of our current piecemeal knowledge with a “greener” contextual knowledge, nor is it a complete paradigm shift, which would most likely be met with much resistance so that the power of the shift is dispersed and any sense of wholeness lost. Instead: each, small, minute, individual choice should be addressed in a more refined manner and looked at closer and deeper, and needs to be tackled as a dynamically charged prospect to make modest and miniscule shifts in relative balances, thereby converting downward spirals into upward spirals. Such a phenomenological attitude might allow us to see the wholeness that is reflected in each of these choices so that a healing might happen among people, place, and nature.

Thus, such an integrated, holistic approach would be incorporation of authentic biomimicry rather than simply being “green.”

4.5.3 Conclusions on Biophilia

Biophilia: Initial Hypothesis and Summary

The research assists and promotes the incorporation of “green, living façade systems”, and assesses the potential benefits of bio-design in building envelopes as a tool in improving the health and viability of buildings in coastal communities. Psychophysiology (the mind-body-

interaction) utilizing experimental protocol in controlled, laboratory setting is used as part of the final testing and analysis, to assess people's responses to nature-inspired design and biophilic architecture. ECG (heart rate), SCR (skin conductance), EMG (facial muscular responses), and EEG (alpha component) are used as specific measures to determine how people perceive and relate to "green façades" in Hawaii.

The Biophilia Hypothesis, introduced by E.O. Wilson, suggests that there is an instinctive bond that exists between human beings and other living systems found in nature. By identifying and understanding people's physiological and emotional responses to biophilic building design in Hawai'i, the findings can be used as a rubric for implementation of nature-inspired designs in other similar sites located in tropical/subtropical coastal areas. It is quite evident that by incorporating elements from nature or "biophilic design strategies", potential deleterious influences can be countered, resulting into more positive affects and more relaxed physiological and psychological states.

Biophilia: Results and Discussion

It stands to argue that whether or not biophilia is the underlying cause for human preference for nature-inspired and natural design elements, the building façade seems to be the ideal place where this type of formal investigation can be integrated. This is not only because we spend a lot of time in built or architectural settings, but also because architecture is also essentially a physical and mathematical undertaking combined with the inclusion of art, with keen interest in proportions among parts and whole.

The human mind is highly interesting in that it recreates those elements that had a significant survival value during its evolutionary history. Furthermore, human creativity is influenced by a wide variety of factors including these impacts of environmental psychology.

With this dissertation, it is clearly evident that biophilic architecture sufficiently stimulates the neural areas that are specialized in processing natural-like forms. Previously, during times when environments were more natural and less urban, there were no inhibitions to form connectivity paths to nature because there was a more profound contact with natural form, and hence the human integrated neural 'biophilic' system received more adequate stimulation. Such a situation contrasts with present-day conditions in modern technologically oriented societies, where contact with natural form has been drastically reduced. From this perspective, it is valuable to encourage architects and designers to work out context-specific design processes and proposals that speak to the evocation of nature and natural forms, in order to revitalize those nature connectivity paths.

In contrast to urban environments, natural contents and landscape configurations are capable of inducing aesthetic preference and stress reduction, and can aid in restoring the ability to direct attention. Such elements are often not present in our living and working environment, or at least they are becoming increasingly less prominent. Such environments thereby deprive humans of a source of wellbeing and pleasure, and of an important restorative power for our psychological, physiological and cognitive functioning. One of the main arguments of this doctorate is that biophilic reactions can be evoked by architectural or design imitations of naturalness. Empirical research indicates that almost exact simulations of nature, and even artistic interpretations of natural settings, are capable of inducing biophilic reactions. Therefore, if it is not possible to integrate real natural contents in a setting, then it could be valuable to implement realistic representations of nature. This discussion underscores the importance of integrating naturalness in our current modern habitats.

4.5.4 Dissertation Research Summary and Final Points

Making all the Connections: Biomorphism, Biomimicry, Biophilia

This dissertation focuses on three components or fields of study: Biomorphism, Biomimicry, and Biophilia through the previous parts of this document. However, it was implemented in parts and now, the synthesis of the whole reiterates the key queries presented earlier:

A) What is the combined purpose of the three components (Biomorphism, Biomimicry, and Biophilia) in achieving design methodologies and implementation processes for sustainable design?

To achieve truly meaningful sustainability that makes interconnections among nature, technology, and humans in the built environment, it was important to first address the “qualifiable” and “quantifiable” objectives of the research:

- 1) Design achieves dynamism,
- 2) Design contributes to homeostasis, and
- 3) Design effectively “reaches back to nature”

B) So, how were these goals addressed in the three sections of Biomorphism, Biomimicry and Biophilia? How is sustainability redefined with the help of this dissertation, using these three

components?

1 = Biomorphism: From the Biomorphism part of the findings in this research, it is clearly observable that there are infinite ways to bring in the natural component into the building façade design. However, the selection of the leaf-to-module analogy is, although by no means exhaustive, complete for the purposes of this dissertation. Admittedly, even though the reader's design processes could be drastically different from the author's perspective offered in the analysis, the obvious conclusion is that there are ways to translate natural forms into building design modules. The design and research exercise conducted in the Biomorphism component was based on the leaf design characteristics of the plant. This morphology concept of the leaf translating into the building design module "set the stage" and was the foundation on which the rest of the components were addressed and analyzed.

Also, the initial design process was influenced by the anticipation of analyses that would, in succeeding components of Biomimicry and Biophilia, be addressed.

Biomimicry (Materials) dealt with the theoretical exploration of possibilities in nanotechnology and advanced materials. Biomimicry (Performance) addressed passive design and thermal comfort strategies by evaluation of the daylighting and natural ventilation adaptations and performance of the design modules. In anticipation of the Biomimicry component, the design modules were created to respond to potential environmental conditions of light and wind. The Light response design was the Rectangular (A) module; Module A responded by changes in angle of the individual building modules, as well as through an adaptation of the building skin to the changes in light source. The Wind response design was the Organic (B) module; Module B responded to changes in wind direction and intensity by altering the surface porosity (from 0 to 90%). The Hybrid Module (AB) was a design iteration that resulted from a combination of Modules A and B. Therefore, the design enabled the modules to change both angle and porosity, and flex the building skin surface, to respond correspondingly to the changes in light and wind.

The Biomorphism component was also conceptualized based on the objectives of the Biophilia component of this dissertation, namely to consider people's "pre-cognitive" physiological (ECG, EMG, SCR, and EEG) and "cognitive" psychological (questionnaire) responses to passively sustainable building envelopes that were designed based on principles of Biomorphism and Biomimicry. The author's objective to assess the "value" of nature-based design had to be performed against the backdrop of non-natural design iteration; thus, the shape and form of the

modules (Rectangular = traditional design, Organic = nature-based design) were a result of this iterative design process.

2 = Biomimicry (Materials): An extensive research into nanotechnological applications was based also on the initial Biomorphic hypothesis of relating the leaf to the building module. In this case, the nanomaterials were looked at using a “different lens” or vantage point, of changing the scale of research and investigation. While the other components of this dissertation looked at the macro properties, this component took a close look at the same “leaf-to-building” analogy, but in a vastly different manner. Again, anticipating the overall research objectives and analysis that would follow in successive components, the materials section investigated and delineated specific nano strategies that would assist the design principles of a passive design employing concepts of daylighting, natural ventilation, and thermal comfort. These strategies investigated included concepts of biomimicry (Daylighting = Heliotropism, Photoperiodism; Natural Ventilation = Stomatal Transpiration, Thigmonastic Movement; Thermal Comfort = Shape Change and Color Change for Thermoregulation). These strategies were then linked back to the Biomorphism component to identify the areas within the building façade and individual design modules that would be conducive to accepting and implementing the nanotechnologies, should they become available in the future for architectural projects.

3 = Biomimicry (Performance): Analysis was performed based again on three measures: Daylighting (Illuminance in lux), Natural Ventilation CFD (Resultant wind speeds in m/s, and cell pressures in Pascals), and Thermal Comfort (heat gain charts and temperature bands in deg.C). Post-analysis measures checked the three proposed design modules for a different kind of “responsiveness”, i.e, measured the ability to adapt to changes in environmental conditions through different times of the day and year. Analysis and measures revealed that the Hybrid Module (AB) was the most ideally adapted to light, wind and heat as environmental stimuli. Performance levels of this module, when compared against the other two façade modules (A and B), proved that dynamic responsiveness utilization of alterations in both angle and porosity as adaptive techniques was the ideal method of achieving homeostasis and conditions of equilibrium within the interior spaces of the “Eco-Office”.

4 = Biophilia: The final evaluation lens was achievable through a combination of experiments and surveys. Psychophysiology, over the ages, has been extensively studied for its contributions to measuring human perceptions and responses. This dissertation evaluated the images created

based on the three design modules (A, B, and AB). Respondents were also asked verbally to indicate which images they preferred most and least, and also indicate the reasons why. The “Nature” component and “Dynamism” and “Comfort” levels were found to be ranked higher than pure aesthetics with design images that evoked experiences and relationship with nature. These results corresponded closely with the precognitive measures from the experimental testing, where the majority of respondents were found to achieve healthy indices of physiology, namely: calmness, focus and attention, low stress, and happiness. These measures strongly indicated that nature is extremely comforting, calming, non-arousing, and relaxing to people.

Furthermore, the Biomimicry and Biophilia components strongly attested to the overall premise of this dissertation: that nature and nature-based environments are superior to conventional design processes in a variety of ways so that a sustainable design created out of a combination of Biomorphism, Biomimicry, and Biophilia does indeed accomplish the following goals:

- 1) Achieves dynamism,
- 2) Contributes to homeostasis, and
- 3) Effectively “reaches back to nature”

Implications of the Research

It is now crucial to take a step back, and ponder over the research goals, and define and summarize briefly the nature and conclusions as observed from the author’s perspective of working through the dissertation components. This dissertation work and the design of the ‘ECO OFFICE’ will serve as:

- A. Guide for sustainable architecture within the tropics that can incorporate design efficiency strategies from BIOMORPHISM.
- B. Guide for sustainable architecture within the tropics that can incorporate maximum Daylighting, Natural Ventilation, and Thermal Comfort strategies from BIOMIMICRY and NANOTECHNOLOGY.
- C. Guide for designing built environments that evoke and arouse BIOPHILIC connections, and thus POSITIVE PSYCHOLOGICAL RESPONSES in people.

The digital prototype and research base can be used as stepping-stones for more advanced analysis along similar lines of inquiry. The applications for such a study are multifaceted and will serve to educate architects, researchers, and communities on sustainable design, and can influence

policy makers and planners to consider comfort and passive design strategies, with a core focus in ecologically responsive and socially responsible methods and practices. Clearly, the work proposed will be a valuable asset to many people in the field of architecture, technology, urban design and environmental aesthetics.

1) The Vantage Points

What is the underlying intent of this research? What is the major contribution of this research?

The singular, most important aspect of this dissertation and the design application is the novelty of the “vantage point”.

Conventional methods of achieving sustainability in design have involved the consideration placed to the intrinsic “wholeness” of a building. Although this has been successful with the simultaneous utilization of various rating systems and methods (LEED point distribution and LBC prerequisites, section 2.1), the facts that remain largely undisputable with current design practices and methods of analysis, and have been analyzed in this research, are as follows:

- A) While there is a theoretical discussion regarding design aspects sometimes viewed as “extraneous” to a typical project and site, the design process and implementation generally does not involve an interdisciplinary vantage point.
- B) Another vantage point that is typically lost, somewhere along the design process, is that of expanding and aiming for a building-environment-symbiosis that “speaks” to natural form, function, materials, and processes; a wholeness that responds to the environmental variability that is evocative of nature.

The vantage points chosen and researched, for the purposes of this dissertation, are not merely from a single “perch” that follows traditional methods, but rather offer a novel, interdisciplinary perspective culminating in the adoption, integration, investigation, and finally an evaluation of design results.

Similar to the way in which nature operates, this dissertation has undergone an evolution, where preliminary theories have been addressed and analyzed, and results discussed from different vantage points.

The vantage points have been multifaceted as well:

- 1) Widely ranging in disciplines (architectural design, biology, ecology, material science, technology, physiology, environmental psychology)
- 2) Varied in scales and levels (urban, building and site, nano molecular)
- 3) Mixed-methods of research analyses (observational and interpretive, literature view and theoretical, case studies and models, qualitative, simulation and modeling, experimental)

2) Integration and Connections

Why is it even imperative to consider an integrated approach of Biomorphism, Biomimicry, and Biophilia, while designing built environments?

Time and again, designers of the built environment have paused to take stock of the current trends in development, reassess goals and strategies, and accordingly adjust design approaches to achieve paradigm shifts in the process of creating and realizing their goals. The objective of “raising the bar of sustainable design” has led to significant advancements in green design and energy efficiencies, and maintaining a minimal impact on nature’s resources. “Net-zero” projects, although admirable for their commitment to tread lightly on the environment, have also been somewhat limited in their approaches to a holistic design process.

This dissertation work, takes one step beyond the LEED standards and the Living Building Challenge, and paves the way toward an all-encompassing work on positive-impact design process. From start to finish, the emphasis has been placed on considering and incorporating these several vantage points. Furthermore, as has been reviewed and demonstrated in the previous chapters, there is an inherent “sense of happiness”, a reconnection that leads humans to bond with nature and living, dynamic forms and functions. A sincere attempt has been made by the author to establish these connections, and to promote the ideal architectural vision of built environments:

- That not only structurally support the inhabitants, but also support life within
- That are not simply machines that maximize energy and water efficiency, but also speak to the dynamics and environmental characteristics, that are an inherent part of nature
- That are not just “churners” of highest output and productivity among the occupants, but also reach them at a subconscious level and instill happiness, stir the soul, enhance creativity

3) What next?

How might this design approach change our relationship to the environment or our view of nature? How does this project potentially revolutionize the way we design our buildings?

The future is now. With advancements and everyday discoveries being made in sustainable material technologies, we can now easily envision a future that involves passive, futuristic technologies that run on clean energy (no biofuels), that is able to achieve a “bottom-to-top approach” with material (re)uses, and utilizes the subtlety of nature’s signals and cues to activate building components. Much like muscles that bend and flex in response to the stimuli, and similar to trees and leaves that lay static, and yet are instantly compelled into action potentials upon the slightest touch, it is now possible to imagine and strive toward truly dynamic, living, breathing buildings and urban environments.

This dissertation aims to retrace the innate appreciation that humans have for nature and life, and carry that concept forward to use in building design and technological applications. A genuine transformation is hoped to be one of the results of the author’s work through this dissertation; a transformation of awareness and a renewed understanding of the true meaning of sustainability, and a cognizance of the ways by which a positive-impact, passive-energy, and an integrated concept of Biomorphism, Biomimicry, and Biophilia, can be accomplished. It is neither an unattainable nor a fantastical premise; the design concepts, applications, and implementation methodologies that have been proposed in this dissertation serve a noble purpose: that of being able to interact with nature at all levels and in all forms, so much so that the transitions between home, workplace, and the outdoors are almost non-existent.

The possibilities are staggeringly endless. Oftentimes, innovations and discoveries provide the means to delve past the banal and the superficial; in the case of this research, these discoveries and analyses lead back to the roots of the human-nature relationship. There is a readily apparent simplicity, elegance and intelligence that natural organisms and living beings convey, to people of science and to laypersons alike. This instinctive and collective consciousness is almost spiritual in its ability to reach and spread fingers of sentience outward, to the environment. Such concepts and strategies, when translated into the built environment, seem to unfailingly arrive at solutions that are complex and yet ingeniously simple, multifaceted and yet coherent. The focus is on the path (means), and not the end.

To comprehend the resplendence and beauty of nature, it is not necessary to have a foreknowledge of the forms and processes that make natural systems possible; however, arming oneself with such expertise is all the more awe-inspiring for the understanding that the new knowledge provides. Similarly, designers and architects can be instrumental in deepening people's connections to the environment, when they design with the forethought and challenge their imaginations to face new frontiers, to synthesize multiple perspectives or "vantage points", look beyond currently established norms and practices of sustainable processes.

Looking to natural forms for inspiration, managing resources efficiently, employing models that builds to reinforce a greater, larger vision from each and every miniscule decision: these form part of an overall rubric that should be adhered to, if relevant progress is to be made in sustainable and green design principles.

The intention of this dissertation is multifold: while design processes, schematics, and detailed analyses can be identified with the triad system of Biomorphism, Biomimicry, and Biophilia, the intention is not to merely provide a comprehensive analysis of sustainable design, but to additionally point out and rectify a reoccurring deficiency that exists with the sustainable design process—namely, a focus on calculative methods and systems that mimic nature to reduce human impact on nature. It is the contention of the author, with the work of this dissertation that, without a deeper connection among people, nature, and the built environment, many of the proposed solutions for ecological design and sustainability merely lessen the impact on the environment and will be an inadequate measure of satisfying profounder and loftier goals, similar to the ones in this dissertation, of achieving a self-sustaining, sustainable, and well-functioning community and urban civilization.

Apart from a number of positive consequences, there are also possible downsides of growing urbanization: in particular, the loss of natural forms in the modern human living environment. Humans are, in a sense, genetically predisposed to affiliate with nature. Humans are also constantly adapting to new technologies. The combination of novel, context-appropriate technological innovations with biomorphic, biomimetic, and biophilic design elements can be indeed a quite powerful tool for designers to wield. Rewiring humans to nature through these different ways helps to restore the interconnectedness that is readily apparent.

Criticisms and Validation

It should be noted that there is a fair amount of speculation and hypothetical theorizing by the author regarding the three topics: Biomorphism, Biomimicry, and Biophilia, as they relate to sustainable design processes, strategies, and general principles.

Where possible, the chapters through the body of this dissertation have been part of an attempt to support these hypotheses with the following research devices:

1. References to evidence-based design and study of empirical research and literature
2. Qualitative approach through phenomenological techniques
3. Quantitative analysis by using software simulations, experimental testing, and statistical analysis.

One primary criticism regarding this dissertation is that there still exists grey areas or unidentified entities within the analysis of “looping”. By this, the author implies that, while there is a clear picture of flow and interconnectedness from the external (nature and environment) --→ to the internal (the building, site, context) environments, there is perhaps a need to address the complexities that exist in the reverse direction (internal to external). This question calls for resolutions on how this combination of Biomorphism, Biomimicry, and Biophilia on building façade designs could in turn affect and effect changes and adaptations in the environment. However, in this regard, the author maintains that there exist solutions that are clearly evident if one looked closer at the dissertation process, methods of inquiry, and analysis.

The comprehensive nature of this research and project application, with the inclusion of Biophilia, theorizes and experimentally validates the initial hypotheses of “wholeness” of the design inclusion processes. Biophilia is the validation measure that reconnects or “re-loops” the design created from Biomorphism and Biomimicry, and the three components together help to evaluate the context and applicative methodology by “testing” it back against the backdrop that is the combination of surrounding natural and urban, built environments.

Future Steps

This dissertation has some distinct advantages that qualify for a decidedly holistic method of envisioning built environments. Typically, for a multidisciplinary approach such as one seen in this dissertation: the major focus is on commonalities, while individual differences are obscured and remain largely un-discussed.

However, the analysis methods, tools, and devices (literature review, empirical findings, software simulations, experimental testing, statistical analysis) utilized in this research have lent several layers of authentication, and have together served as the foundation on top of which future research could serve as verifiable add-ons.

It is also pertinent to note that, while incorporating these additional lines of thought and analysis, there is a need to keep the context or the “sense of place” intact and also to keep unique for future contemplation. General points of note, or design principles, shall serve well as guides for establishing new points of research; however, it is also the contention of the author that the results of the analysis performed within this dissertation are by no means static or constant, neither are they final or exhaustively conclusive. Similar to the dynamic façade modules that form and inform the design applications in this dissertation, there is also an inherent dynamism in the literary and applicative aspects. Students, researchers, and other scholars that will incorporate other means of inquiry relating to points explored in this research, will stand to benefit from this perspective of maintaining a “genius loci” aka, a “sense of place” with their design and theoretical endeavors. For architectural or urban projects that pertain to the broad public sphere (e.g. hospitals, commercial spaces, retail areas), such general findings can be very useful. Furthermore, the more intimate understanding of elements within the private sector or design sphere is also facilitated by the analysis gained from the particularities and individual points of understanding.

Final Note

One of the arguments of this research is to foster, nurture, and actively promote a lifelong, meaningful relationship among people, place, and nature; hence, any sustainable approach, including Biomorphism, Biomimicry, and Biophilia will not only replace conventional practices that involve attempts to reduce negative impacts of the human-made on the natural, but also stimulate an evocative evolution of built environments, and point to a positive impact future with a strong methodology: one rooted in multidisciplinary practices involving the inclusion and comprehension of Nature in all modes and phases of the design.

Implementing such a multidisciplinary and detailed research and design application, through the integration of Biomorphism, Biomimicry, and Biophilia, will not only point the path toward a passive (non-mechanical) approach to achieving positive ecological footprint, but also help ultimately overcome overall environmental issues, such as greenhouse effects, global warming, or

and other destructive climatic changes: by lessening the vastly escalating amount of CO₂ emissions from human-made materials, and furthering a cathartic treatment of the surrounding environments. It is predicted that the approach, methodology, results and findings from this dissertation are not merely desirable for adapting to further research add-ons, but will form a necessary set of tools to use in this 21st century and we have to understand these tools well in order for them to be used in the right manner and for the overall nature – urban – human symbiosis.

The time has now arrived to create a synthesis and symbiosis of design practices and processes involving nature, science, technology, culture, and art.

“We see the world piece by piece, as the sun, the moon, the animal, the tree; but the whole, of which these are the shining parts, is the soul.” ~ *Ralph Waldo Emerson.*

PART 5

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